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Depth and Geographical Distribution of Deep-Focus Earthquakes. By Beno Gutenberg and C. F. Richter.

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FIGURE 1. PHOTOGRAPH TAKEN BEFORE HURRICANE
Showing cottages on east end of Napatree Beach.

FIGURE 2. PHOTOGRAPH TAKEN AFTER HURRICANE
Looking west along Napatree Beach. Cottages shown in Plate 1, figure 1, all of which were built on that part of the beach shown in this photograph, have been completely destroyed. Two groins in the foreground are the same as those in Plate 1, figure 1.

NAPATREE BEACH BEFORE AND AFTER HURRICANE

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 50, PP. 1357-1370, 7 PLS., 6 FIGS. SEPTEMBER 1, 1939

SHORELINE CHANGES IN RHODE ISLAND PRODUCED BY HURRICANE OF SEPTEMBER 21, 1938

BY ROBERT L. NICHOLS AND ALWYN F. MARSTON

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ABSTRACT

On September 21, 1938, a hurricane struck New England. Great property damage resulted from the high winds, and severe floods, but especially from the storm tide, which, topped by a hurricane surf, caused greater loss of life and more coastal damage than had ever before been experienced on the North Atlantic seaboard.

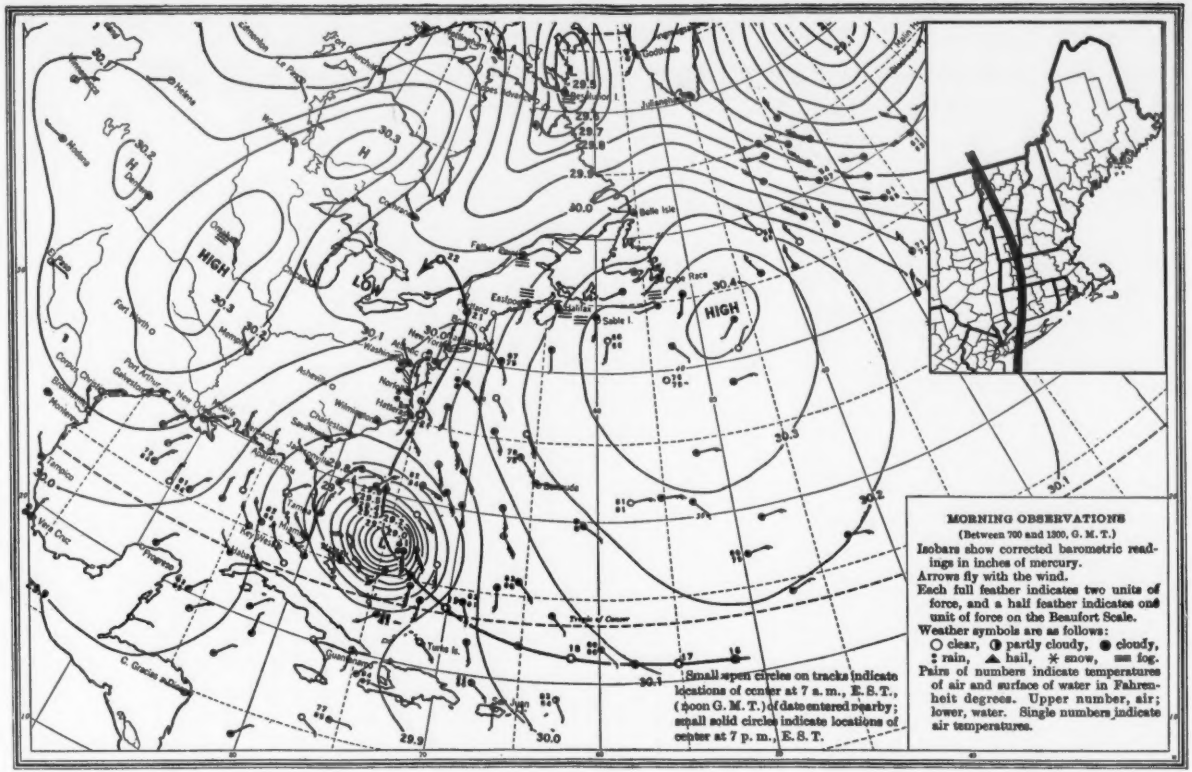
MORNING OBSERVATIONS
(Between 700 and 1300, G. M. T.)
Isobars show corrected barometric readings in inches of mercury.
Arrows fly with the wind.
Each full feather indicates two units of force, and a half feather indicates one unit of force on the Beaufort Scale.
Weather symbols are as follows:
○ clear, ◑ partly cloudy, ● cloudy,
⁝ rain, ▲ hail, ✳ snow, ≡ fog.
Pairs of numbers indicate temperatures of air and surface of water in Fahrenheit degrees. Upper number, air; lower, water. Single numbers indicate air temperatures.
Small open circles on tracks indicate locations of center at 7 a. m., E. S. T., (noon G. M. T.) of date entered nearby; small solid circles indicate locations of center at 7 p. m., E. S. T.
HIGH
LOW
Belle Isle
Cape Race
Sable I.
Hatteras
Charleston
Bermuda
Key West
Tampico
Vera Cruz
Progreso
Turks Is.
C. Gracias a Dios

FIGURE 1.—*Track of the hurricane*

Weather map of North Atlantic Ocean for September 20 and track of hurricane from September 16 to 22. Inset: Path of center of hurricane through New England states. After Tannehill.

At the Blue Hill Observatory, Milton, Massachusetts, the maximum 5-minute velocity was 121 miles per hour and for shorter intervals it was in excess of 150 miles per hour. The storm tide at Providence, Rhode Island, was 13 feet 9 inches above mean high tide. This exceeded the previous record of September 23, 1815, by 1 foot 11¾ inches.

The geologic changes to the Rhode Island coast which resulted from the hurricane of September 21, 1938, are: (1) Formation of inlets eroded through the beaches, (2) widening of the beaches by deposition of material on their bayward sides, (3) erosion of the ocean side of the beaches, (4) erosion of the fore dunes, (5) erosion of headlands and cliffs, (6) deposition of beach deposits in bays and marshes in back of the beaches, and (7) conversion of fresh-water ponds into salt-water bays.

Since the hurricane some of the new inlets have been closed, and others have been partially filled. There seems to be no question but that in a few years the beaches will be in essentially the same condition as they were prior to the hurricane.

INTRODUCTION

In the hurricane of September 21, 1938, the beaches along the southern coast of Rhode Island were greatly eroded and modified. There was thus offered an unparalleled opportunity to study the changes produced by such a storm on a coast only infrequently visited by hurricanes of this intensity. The authors confined their observations to about 12 miles of the Rhode Island shore line, although similar effects were produced along the shore from New York to Cape Cod.

ACKNOWLEDGMENTS

The senior author is happy to acknowledge the generous help of Professor Kirk Bryan of Harvard University in the preparation of the manuscript. Dr. Charles F. Brooks, director of the Blue Hill Meteorological Observatory, explained the phenomena to the authors in advance of his own publication. The authors are most grateful for the co-operation of Mr. Lewis R. Greene of Westerly, Rhode Island, from whom the majority of the photographs were obtained. Mr. J. Alexander of Boston, and Mr. George B. Utter of Westerly, Rhode Island, also supplied several of the photographs. Thanks are due to Mr. Lawrence Goldthwait of Tufts College, for aid in the mapping.

METEOROLOGY

The hurricane apparently originated in the region of the Cape Verde Islands. It travelled westward nearly to the West Indies, then curved northward, crossed Long Island and New England, moved up into Canada, made a right-about turn and returned over New England 2 days later with greatly reduced energy, and then crossed Nova Scotia and Newfoundland. The track of the hurricane from September 16 to 22 is shown in Figure 1. The figure also shows that south of Hatteras its speed of progress was between 10 and 20 miles per hour whereas north of Hatteras it averaged more than 50 miles per hour. When it passed between Ber-

muda and the Bahamas, the area of strong winds (30 miles or more per hour) was about 500 miles in diameter. The belt of damage in New England was approximately 150 miles wide. At the Blue Hill Observatory, Milton, Massachusetts, the maximum 5-minute velocity was 121

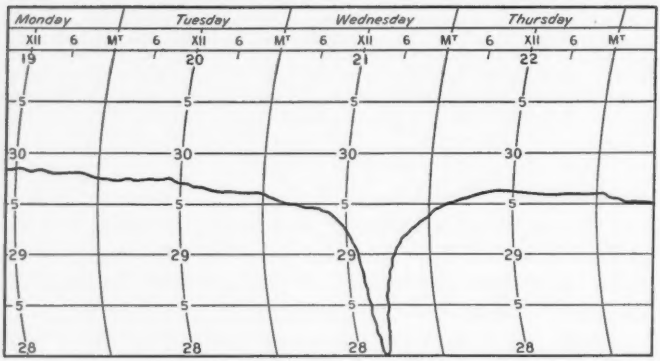

FIGURE 2.—*Record of a barograph located at Middletown, Connecticut, during hurricane of September 21, 1938*

miles per hour and for shorter intervals it was in excess of 150 miles per hour. The destructive winds extended eastward more than 100 miles from the center of the storm, whereas on the westward side they were very much more restricted. This results from the fact that on the east side of the storm the hurricane winds were directed more or less along the line of progression of the storm so that the wind velocities were the result of the combination of the two motions. On the west side, however, the rate of progression was subtracted, because the hurricane winds were moving in nearly the opposite direction. Rain had been falling for about a week in many parts of New England so that, with the additional heavy rains resulting from the hurricane, record floods on many New England brooks and rivers resulted. That the storm came on suddenly and stayed less than 12 hours is dramatically shown by the record of a barograph at Middletown, Connecticut (Fig. 2). The air pressure at the center of the storm was about 28 inches during most of its course over both land and sea. Brooks (1939, p. 120) has listed previously recorded great storms and shows that on the average of once every 150 years New England is struck by a hurricane of an intensity about the same as that of 1938. Detailed papers by Brooks (1939) and Tannehill (1938, 1939) give full information on the meteorological aspects of this storm, and on them the foregoing account is based.

The storm tide at Providence, Rhode Island, was 13 feet 9 inches above mean high tide. This exceeded the previous record of September 23, 1815, by 1 foot 11¾ inches. In the area studied the authors estimated that the storm tide was between 10 and 15 feet above mean high tide. The

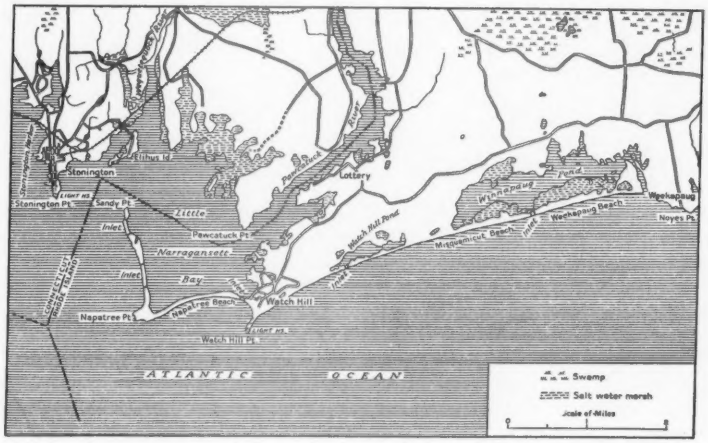

FIGURE 3.—*Map redrawn from part of the Stonington Sheet*

Showing coast from Sandy Point to Noyes Point. Inlets formed during hurricane have been added. Edition of 1893.

factors which contributed to make this abnormal high tide were: (1) The predicted high tide for September 21 was a spring tide, and (2) the hurricane struck the coast at approximately high tide.

GENERAL DESCRIPTION

The area studied consists of 12 miles of the Rhode Island coast, extending from Sandy Point to Noyes Point (Fig. 3). This shoreline is classified by Johnson (1925, p. 105) as moraine shore line and by Shepard (1937, p. 607) as a "glacial deposition coast" modified by marine agencies. Initial irregularities due to submergence of the Harbor Hill moraine have been so modified by the formation of wave-built features and by erosion of the headlands that the coast is in the submature stage. Napatree Point is a tied island, composed of till and fluvio-glacial deposits which are veneered with wind-blown sand derived from the fringing beaches. It is joined to the mainland by Napatree Beach, a tombolo. Sandy Point is a spit attached to Napatree Point. From Watch Hill Point to Noyes Point there are several bay-mouth beaches behind which

are fresh-water ponds, similar to Watch Hill Pond prior to the hurricane, and also a large salt-water pond called Winnapaug Pond. The position of the inlet to Winnapaug Pond previous to the storm and similar positions of the inlets of the bay-mouth beaches farther eastward indicate that the prevailing shore current is from the southwest. The beaches are fairly stable, as bedrock veneered with till crops out at Noyes Point. Watch Hill Point and Napatree Point are protected from excessively rapid erosion by a pavement of huge boulders derived from the till composing these headlands.

PROPERTY DAMAGE

Some idea of the loss of life and magnitude of property damage can be obtained from the Red Cross report of October 21, 1938. According to this report, 488 were killed; 1754 were injured; 93,122 families suffered economic loss; 15,743 families needed assistance; 1991 permanent dwellings, 6933 summer dwellings, and 9807 other buildings (including barns) were destroyed; 72,906 buildings were damaged; 2605 boats were wrecked and 3369 were damaged; and much stock and poultry was lost.

The total economic loss is between $250,000,000 and $330,000,000. Tannehill (1939, p. 50) writes:

> "Indeed, there is little doubt that the value of property destroyed by wind and water attending the New England hurricane of last September was greater than that recorded in any other tropical cyclone in the world's history."

However, this record destruction was not due alone to the unusual severity of the hurricane but primarily to the fact that it crossed a wealthy and densely populated area, in which no provision for such high winds and tides had been made, as there had been no similar storm since 1815.

The expensive summer cottages on Napatree Beach (Fig. 3) are well shown in Plate 1, figure 1, a photograph taken prior to the hurricane. At the height of the storm the beach was probably covered by between 5 and 10 feet of water. That this high water together with the hurricane surf was responsible for the complete destruction of the sea wall and every one of the 44 cottages on Napatree Beach is dramatically shown in Plate 1, figure 2, a photograph taken after the hurricane. More than a million dollars' worth of property and 15 lives were lost in this area.

Misquamicut Beach was the hardest hit, as 369 cottages were destroyed and 41 lives were lost. The extent of the property damage can be visualized by a comparison of Plate 2, figures 1 and 2, photographs taken from the same spot, one before and the other after the hurricane. The only features which can be identified with certainty in both photographs are the two posts which stand about 1 foot above the ground and which can be seen on the left hand side of each photograph. These photographs show

FIGURE 1. MISQUAMICUT BEACH BEFORE HURRICANE
Note the two posts approximately 1 foot in height on left hand side of the road.

FIGURE 2. PHOTOGRAPH TAKEN AFTER HURRICANE
From same place as Plate 2, figure 1. The two posts (circled) are the only features which can be recognized.

FIGURE 3. MISQUAMICUT BEACH AFTER HURRICANE

MISQUAMICUT BEACH BEFORE AND AFTER HURRICANE

FIGURE 1. PHOTOGRAPH TAKEN BEFORE HURRICANE
Exposed position of the Point and the protecting sea wall are shown.

FIGURE 2. PHOTOGRAPH TAKEN AFTER HURRICANE
The sea wall was destroyed and the middle foreground was considerably eroded.

EROSION OF WATCH HILL POINT

that the road was covered with sand, telephone posts were knocked down, and cottages were driven across the beach. The desolation of the scene after the hurricane is well shown in Plate 2, figure 3.

Behind the beaches and stretching for miles along the shores of the marshes and ponds, there was a debris line consisting of beds, chairs, refrigerators, boats, lumber, and houses. A mental picture of the magnitude of this debris line can be gained when one considers that hundreds of homes were swept from their foundations on the beaches and carried inland. Most of this debris was deposited between 5 and 15 feet above normal high tide.

EROSION OF HEADLANDS, CLIFFS, FORE-DUNES, AND BEACHES

In the area studied there are three headlands—Noyes Point, Watch Hill Point, and Napatree Point. Noyes Point is composed of bedrock thinly veneered with till. The Point is in places protected from rapid marine erosion by the bedrock and elsewhere by a pavement of huge boulders derived from the till. During the hurricane, as would be expected, the Point was but slightly eroded. However, the paved road that skirted the headland cliff was considerably damaged in spite of protection by boulders and a sea wall.

Napatree Point, protected only by boulders derived from the till, was considerably eroded. That part of the headland composed of stratified glacial sand was considerably more eroded than that part composed of till. As the stratified sand is flanked on both sides by till, a rectangular re-entrant has been cut in the area composed of sand.

Watch Hill Point is composed of till. It was badly eroded, especially in localities nearest the mainland. The Point might have been cut off as an island but for the protection afforded by the strong sea wall. The magnitude and force of the waves and their capacity for erosion is indicated by a comparison of Plate 3, figures 1 and 2, one taken before the hurricane, the other after.

A short distance from Watch Hill Point a 50-foot cliff composed in the main of stratified sand and protected by a concrete sea wall was stripped of its vegetative cover and eroded as much as 30 feet, as is shown by a comparison of the photographs of Plate 4, figures 1 and 2. This cliff, together with a part of Watch Hill Point, is shown in Plate 4, figure 3, a photograph taken after the hurricane. In many places the storm waves eroded small cliffs, the bottoms of which are nearly 10 feet above normal high tide. Such cliffs, if grassed over and somewhat softened, might be taken, by one unfamiliar with the height of these storm tides, as evidence of a short stand of the sea at an elevation of 10 feet above its present position.

On Napatree and Misquamicut beaches, the dunes, none of which was more than a few feet high, were completely washed away. The fore-dune on Weekapaug beach varied from 25 to 30 feet in height. That this fore-dune was badly eroded—the front retreating as much as 50 feet in places—is shown by a comparison of the photographs of Plate 5, figures 1 and 2. Plate 5, figure 1, taken before the hurricane, shows a summer cottage built on a fore-dune, which extended approximately 50 feet in front of the cottage. The same cottage partially undermined, with the fore-dune completely eroded from in front of it, is shown in Plate 5, figure 2, a photograph taken after the hurricane. The cement foundation under this cottage undoubtedly saved it from being completely undermined and toppled over, a fate which many of the cottages nested in this fore-dune suffered (Plate 5, figure 3). In some places channels were cut through the fore-dune; in others where the dune was low, it was completely washed away (Plate 5, figure 2). Behind these breaks there have been deposited great scallops of sand, which extend out over the marsh as much as 750 feet from the eroded fore-dune. A measure of the amount of sand eroded from the dune and beach can be obtained by noting the extent and depth of these scallops. An unknown portion of the sand was undoubtedly washed back into the sea.

Napatree Beach was considerably lowered, and its ocean side was retrograded in places as much as 40 feet during the hurricane. The beach was extended and widened on its bay side by the deposition of part of the material thus eroded. Little Narragansett Bay was also considerably shallowed by sand washed over this beach. Already the beaches have begun to be prograded and they will soon occupy approximately the positions they had before the hurricane, as erosion to the headlands has been negligible. The fore-dune, too, will eventually extend itself forward by the accumulation of wind-blown sand in front of the recently eroded cliff. This process has already begun since the hurricane, but its completion will require many years.

INLETS

DESCRIPTION OF INLETS

That the beaches were breached in scores of places is well shown by Plate 6, figures 1 and 2, both of which are photographs taken after the hurricane. Plate 6, figure 1 is an aerial photograph of Weekapaug Beach showing the partially destroyed Weekapaug Inn and at least four inlets. A small tidal delta has been built on the bayward side of the inlet immediately behind the inn. Although this photograph was taken only a few days after the hurricane, it shows that the inlet in the foreground had already started to heal on the ocean side. Plate 6, figure 2 is

FIGURE 1. A 50-FOOT MARINE CLIFF AT WATCH HILL, RHODE ISLAND
Photograph taken prior to the hurricane.

FIGURE 2. PHOTOGRAPH OF SAME CLIFF TAKEN AFTER HURRICANE
The cliff has been stripped of its vegetative cover and eroded 30 feet.

FIGURE 3. AERIAL PHOTOGRAPH TAKEN AFTER HURRICANE
Showing eroded cliff, Watch Hill Point, and three inlets cut in Napatree Beach. (Official photograph, 2nd Air Base Squadron Photo Section, GHQ Air Force, United States Army, Mitchel Field, N. Y.)

FIGURE 1. PHOTOGRAPH TAKEN BEFORE HURRICANE
A cottage built on the fore-dune of Weekapaug Beach.

FIGURE 2. THE SAME COTTAGE AFTER HURRICANE
The fore-dune was eroded 50 feet during the hurricane.

FIGURE 3. SUMMER COTTAGES ON WEEKAPAUG BEACH
Undermined because of erosion to the fore-dune.

an aerial photograph of Charlestown Beach a few miles east of the area studied; it shows several inlets cut through the beach during the hurricane. The inlet in the foreground has been healed on the ocean side although this photograph was taken only a few days after the hurricane.

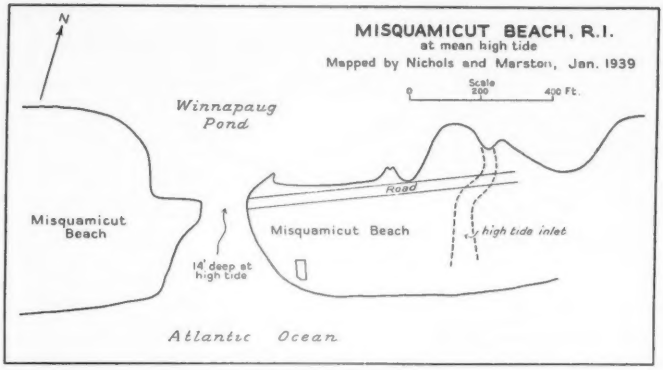

FIGURE 4.—*Plane-table map of inlet cut in Misquamicut Beach*

Map was made in January, 1939.

During the hurricane an inlet 300 feet wide was opened in Napatree Beach, and two inlets, one 1600 feet wide and the other 900 feet, were cut in Sandy Point. A continuous beach nearly 3 miles long was thus broken into three islands with more than half a mile of water between them (Fig. 3). All three of these inlets have been cut more than 4 feet deep at the low-water stage. Moreover, there are many cross channels in Napatree Beach which were not cut deeply enough to contain water at low tide and are therefore inlets only at high tide. Plate 7, figure 1 is an aerial photograph of the Napatree Beach inlet. This inlet has since been filled by the town of Westerly in order to tie the taxable property on Napatree Beach to the mainland.

The 900- and 1600-foot inlets cut in Sandy Point are well shown in Plate 7, figure 2, an aerial photograph taken after the hurricane. At the time when this photograph was taken, the island in the middle of the 1600-foot inlet existed only at low tide. In the few days after the storm, small spits had already grown forward from each side of the inlets into Little Narragansett Bay. The tidal and wave-formed currents which run through the inlets and into the bay are the obvious cause of these spits. However, no spits have been formed on the ocean side of the inlets, as the shore currents have been strong enough to

redistribute material deposited by the tidal currents that run from the bay to the ocean.

Watch Hill Pond has been converted from a fresh water pond into a salt water bay (Fig. 3). As the tidal scour in this inlet is necessarily

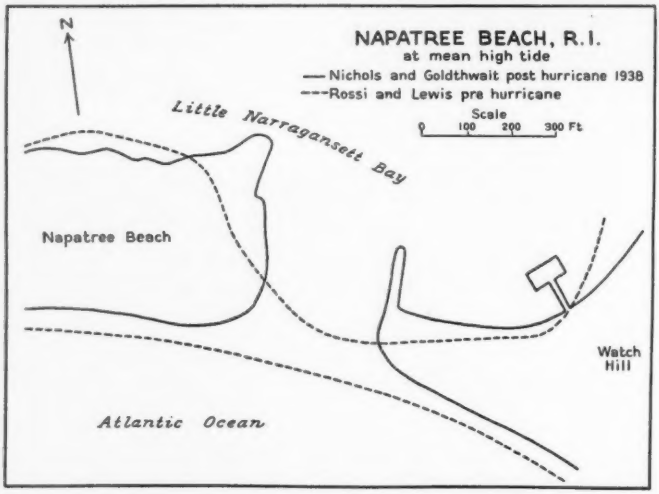

FIGURE 5.—*Map of eastern end of Napatree Beach before and after hurricane*

weak, owing to the small water body drained, the inlet is not so deep as those in Napatree Beach and Sandy Point.

A much larger inlet has been cut in Misquamicut Beach (Fig. 3). That the inlet is 70 feet wide on the bay side and approximately 400 feet wide on the ocean side is shown in Figure 4, a plane table map of the area. Measurements show that the inlet on January 7, 1939, was at least 14 feet deep at high tide.

LOCALIZATION OF INLETS

Factors which might have been responsible for localization of the inlets are: The height, width, and composition of the beach, density of vegetation above the high-water line, and the presence or absence of a sea wall.

Maps of the Napatree Beach inlet area, made before and after the hurricane, are shown in Figure 5. This figure shows that the inlet was cut at the narrowest part of the beach. The maps also show, that the front of the beach retrograded about 40 feet during the hurricane. The

outline of Sandy Point in 1935 and immediately after the hurricane is shown in Figure 6. A comparison of the two maps clearly shows that both inlets were cut where the beach was narrow and presumably low. Both the Misquamicut Beach inlet and the one which converted Watch

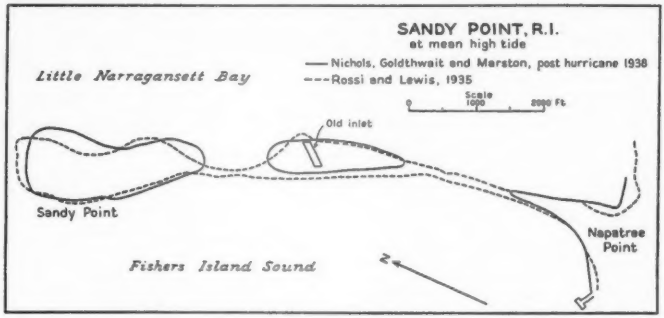

FIGURE 6.—*Sandy Point before and after hurricane*

Dotted line represents Sandy Point in 1935. Taken from map by Rossi and Lewis, city engineers of Westerly, Rhode Island. Solid line shows Sandy Point a few weeks after hurricane.

Hill Pond into a salt-water bay were also cut where the beach was narrow.

We may conclude, then, that the most important factor in the localization of the inlets was the narrowness of the beach.

FORMATION OF INLETS

Although the authors were not present during the formation of the inlets, a clear picture of their formation can be obtained from theoretical considerations and from an examination of the beaches after the hurricane.

As the storm progressed, the water rose higher and higher until finally a wave washed over the top of a low part of the beach. This lowered the beach. Successive waves continued the erosion until finally a current of water was running through it at this point. This current caused further erosion. Napatree Beach and other low beaches which did not have high fore-dunes on them were completely covered by between 5 and 10 feet of water at the height of the storm. The passage of this water across the beaches lowered them generally along their entire extent.

That the beaches were eroded by water which passed over them from the ocean side is proved by the following facts: (1) In many cases the beaches were extended bayward; (2) houses were carried from the

beaches far inland; and (3) the bays and ponds in back of the beaches were considerably shallowed by deposition of material eroded from the beaches.

Finally the crest of the storm tide was reached, and water began to flow back across the beaches. Since the storm tide was between 10 and 15 feet above the normal high tide and since the tidal range of this area is about 5 feet, it is obvious that a quantity of water at least 15 feet deep over the bays and ponds had to flow back either across the eroded beaches or through the inlets. This movement further eroded the beaches and inlets, both those that existed originally and those that had been newly cut. Water continued to run through the deeper inlets after it had stopped running across the beaches and through the shallower inlets. They were thus differentially eroded. The material eroded from the beaches and inlets by the ebb tide has been redistributed on the sea floor by the long-shore currents so that its identity has been lost, whereas the material eroded by the flood tide has extended the beaches bayward and filled in the ponds and bays. The origin of the new inlets may be summed up by saying that wave erosion initiated them and that tidal currents enlarged them.

HEALING OF INLETS

As is well known, a conflict starts as soon as an inlet is formed in a beach. Tidal currents going through the inlet tend to keep it open, while at the same time the waves and shore currents, aided by the wind, tend to close it by deposition of sand. The relative strength of these forces determines the speed with which any inlet will heal. The strength of the tidal currents depends in the main upon the tidal range, the area of the bay back of the inlet, the volume of water contributed to the bay by streams, and the depth of the inlet—in other words, on the volume of water going through the inlet. The strength of the waves and shore currents depends upon the exposure of the beach and the fetch of the waves. As the balance of forces varies from one inlet to another, it follows that some inlets will heal more quickly than others.

As the tidal current going through the inlet into Watch Hill Pond is weak because the volume of water in the pond is relatively small, it seems reasonable to conclude that the inlet in this beach will soon be healed. The inlets in Sandy Point can be healed by material deposited in them by currents operating on both sides, either in Fishers Island Sound or in Little Narragansett Bay. In other words, they can be healed by currents generated by winds from practically any direction. As the inlet in Misquamicut is healed only when the wind is from the southerly half and as the inlet is deeper than those on Sandy Point, it seems reasonable to predict that those in Sandy Point, even after tak-

FIGURE 1. AERIAL PHOTOGRAPH OF WEEKAPAUG BEACH TAKEN AFTER HURRICANE
Showing the badly damaged Weekapaug Inn and several inlets.

FIGURE 2. AERIAL PHOTOGRAPH OF CHARLESTOWN BEACH
Showing several inlets, some of which are partially healed on the ocean side.

INLETS IN WEEKAPAUG AND CHARLESTOWN BEACHES

FIGURE 1. AERIAL PHOTOGRAPH OF 300-FOOT INLET CUT IN NAPATREE BEACH
A tidal delta on bay side of inlet can be seen. Groin in lower right hand side of photograph is the same as that in Plate 1, figures 1 and 2.

FIGURE 2. AERIAL PHOTOGRAPH OF SANDY POINT
Taken a few days after the hurricane. Little Narragansett Bay is on the right, Fishers Island Sound on the left.

INLETS IN NAPATREE AND SANDY POINT BEACHES

ing into consideration their greater width, will be healed before the one at Misquamicut. Observations made since the formation of these inlets substantiate these theoretical conclusions. The 900-foot inlet in Sandy Point was only 30 feet wide at high tide on December 19, 1938. On January 7, 1939, it was completely closed by the growth of a spit on the Fishers Island Sound side. The spit grew northward from the Napatree Point side of the inlet. The growth of a spit from the south northward is what would be expected as Sandy Point is protected by the mainland from the northwest storms while it gets the full force of the southwest storms. Erosion of the beach immediately south of the inlet furnished the material for the spit. That this part of the beach has been eroded in the last three months is indicated by the following facts: (1) The fore dune has been eroded during this period; (2) this part of the beach has retrograded between 50 and 100 feet during this period; and (3) peat now outcrops on the beach where heretofore it did not. On January 7, 1939, the 1600-foot inlet in Sandy Point was much shallower than it had been when the authors observed it in October, November, and December of 1938. A spit had grown into the inlet from the northern side. The island (Pl. 7, fig. 2) was much larger and was not completely covered even at high tide. It is quite obvious that this inlet will soon be filled if there is no artificial interference.

The inlet at Misquamicut, however, has shown no tendency to fill in since it was formed. On January 7, 1939, a current carrying sand in susupension and having a velocity between 4 and 5 miles per hour was running through it.

Prior to the hurricane, Winnapaug Pond (Fig. 3) had one inlet; it now has two, It seems reasonable to suppose that when these beaches are again stabilized it will have but one. Since the new inlet is closer to the main body of the water in the pond, it seems likely that if there is no artificial interference the new break will maintain itself and the old one will be filled in.

A channel partially filled with marsh vegetation cuts diagonally across Sandy Point (Figs. 3 and 6). Beach ridges have been built across both the Fishers Island Sound and Little Narragansett Bay ends of this channel. This feature in essentially its present condition is also shown on the 1839 United States Coast and Geodetic Survey chart of this area. If this channel is an old partially filled inlet, which seems likely, it indicates that inlets which have been cut through a wide part of a breach take a long time to fill completely. This inlet may well have been formed by the 1815 hurricane. That such an inlet fills in very slowly is due to the fact that after beaches are built across both its ends the middle part can be filled only by the accumulation of vegetation, by the

deposition of wind-borne material, and by washing in of material during exceptional storms.

CONCLUSION

Although the changes caused by the hurricane of September 21, 1938 were greater than those resulting from many years of winter storms, it seems likely that in a few years the beaches will be in essentially the same condition as they were prior to the hurricane. The new inlets are being closed, the salt water ponds formed during the storm are reverting to their former fresh water condition, and the fore-dunes have started to build themselves forward. The net result was a widening of the beaches by the deposition of material on their bayward sides, the erosion of headlands and cliffs, a very slight retrogression of the beaches, and the deposition of beach deposits in the bays and marshes in back of the beaches.

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GLACIAL GEOLOGY OF BOULDER MOUNTAIN, UTAH

BY LAURENCE M. GOULD

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ABSTRACT

Boulder Mountain is the easternmost part of Aquarius Plateau. Physiographically it is virtually an independent plateau with an area of about 70 square miles and an altitude which approximates 11,000 feet. The remainder of Aquarius Plateau lies 1000 feet lower and is set off from Boulder Mountain by the westward-facing scarp of the latter. The plateau top is covered with a succession of lava flows from which great landslides have descended to cover the plateau flanks on all sides.

The nearly flat surface of Boulder Mountain is largely covered with a maze of small lakes interspersed with broad shallow depressions or "meadows." Most of the lakes occupy glacially scoured rock basins, none of which exceeds a quarter of a mile in length. Striations and grooves are abundant, and glacial polish was seen in a few places. The plateau top was covered with an ice cap during Pleistocene time, which grew so large that it spilled over the rim on all sides. Avalanche ice and reconstructed glaciers, as well as sizable ice tongues or outlet glaciers, must have been common. Most of the overflow was stopped when it reached the first sizable landslides below the rim. As a result there are numerous lakes under the rim which are clearly the result of the combination of landslide dams modified by glacial action. A few ice tongues were strong enough to plow their way through the landslides and leave behind broad, very shallow U-shaped valleys which are now occupied in places by morainal lakes. No undoubted glacial deposits were found below 8950 feet.

INTRODUCTION

Boulder Mountain is the name given to the northeastern section of Aquarius Plateau (Fig. 1), which in itself constitutes the southern part of the inner or eastern range of the High Plateaus of Utah. In some

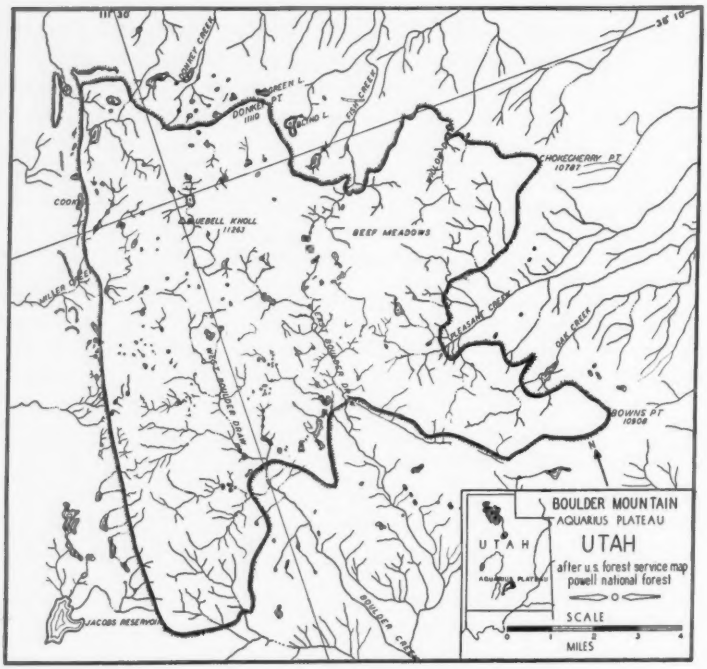

FIGURE 1.—*Outline map of Boulder Mountain*

respects Boulder Mountain is a separate plateau, for not only does it rise to heights of 11,000 feet above sea level so that it stands from 5000 to 6000 feet above the desert country to the south, east, and north, but likewise it rises approximately 1000 feet, in a westward-facing fault scarp, above the remainder of Aquarius Plateau. The United States Forest Service recognizes the notable differences between these two regions and on its maps restricts the name Aquarius Plateau to the lower portion which stretches to the southwest from this fault scarp, and labels Boulder Mountain as a separate feature. This is a desirable use of terms from a physiographic standpoint.

The field work upon which this paper is based was made possible by the friendly cooperation of Reed Bailey, Director of the Ogden Experiment Station of the United States Forest Service, Allan Folster, Supervisor of the Powell National Forest, and Ranger Wilford Bentley of the same Forest. To the latter the writer is especially indebted, for without the direct assistance given by him, together with his expert knowledge of the geography of the whole area which was always available, the field work could not have been completed.

The first and only geological studies reported from Aquarius Plateau are contained in the report by Dutton (1880, p. 284-289). The Plateau, including Boulder Mountain, was visited by Helen Dixon (1936, p. 272-320) as a part of her ecological studies of the High Plateaus.

GENERAL GEOLOGY AND GEOGRAPHY

GENERAL CONSIDERATIONS

From a distance Boulder Mountain presents an even, expressionless skyline. It appears to be a simple tabular-topped mountain of massive cliffs, at the bases of which are great accumulations of talus. A closer approach demonstrates that this simple form is an illusion, for the apparently formless character of the mountain top changes into gigantic, flat-topped spurs, extending out into the desert country and parted by deep valleys, some of which have been modified by glaciation.

The plateau or mountain top is covered with a succession of basaltic lava flows totaling from 1000 to 2000 feet in thickness, the topmost of which, at least, are vesicular. These extrusive sheets are underlain by Tertiary sediments. The uplift of Boulder Mountain above the remainder of Aquarius Plateau was not accommodated by deformation along a single fault plane but rather by differential movement along a number of planes. In some places detached parts of Boulder Mountain rim are separated from the parent mass by a sort of graben (Pl. 1, fig. 1). In other places one descends from the mountain rim to the main body of Aquarius Plateau by ill-defined slump steps, the highest one of which lies about 400 feet below the rim.

The remainder of the rim, on the north, east, and south, consists of massive cliffs produced by the recession of the hard flat-lying cap rock. On all sides the intimate relationships between the lavas and the sediments below are obscured by great landslides, or slumps, to use the more exact word according to Sharpe (1938, p. 65). Successive masses of the rim have slid down to form a series of step-like features or "terracettes," some of which have back slopes (Pl. 1, figs. 2 and 3). Rock falls and talus accumulations of various sorts, including pro-talus (Sharpe, 1938,

p. 43-44) or nivation ridges, are universally present about the base of the rim rocks.

Thousand Lake Mountain, north of Boulder Mountain, is its complete counterpart in structural and stratigraphical relationships. In fact the two were once a continuous feature, and Thousand Lake Mountain is but a small edition or detached remnant of the once larger Boulder Mountain. The erosional activity of Fremont River has brought about the separation. Plate 1, Figure 2 shows Thousand Lake Mountain in the distance. This tabular-topped mountain illustrates the essential character of Boulder Mountain better than any photographs which can be made of the latter, much larger feature. The general slope from the plateau rim to the desert country round about, as revealed in this picture, is an inheritance from Tertiary erosion, according to Gregory and Moore (1931, p. 135). Present stream cutting is gradually dissecting and destroying these slopes about Boulder Mountain.

TOPOGRAPHY AND DRAINAGE

The term "mountain" seems a misnomer when one is on top of Boulder Mountain. Numerous aneroid readings showed but few differences in altitude, between basins and nearby knolls, that approached 50 feet. The highest elevation is 11,263 feet, and the whole approximates an average of 11,000 feet above sea level and covers an area of nearly 70 square miles.

The topography is a bewildering maze of low glaciated ridges and roches moutonnées alternating irregularly with scour basins, relieved in places by broad shallow basins, or meadows (Pl. 2, fig. 1) as they are locally called. Swampy, sedge- and grass-bordered ponds, connected in some areas by sluggish streams, occupy the lower parts of the meadows. Many of the scoured rock basins are lake basins.

Though the country around Boulder Mountain is characterized by a radial drainage pattern with streams heading in the plateau, this pattern is not conspicuous on top. On the contrary it is the general lack of form, or the haphazard and imperfect manner of the drainage, which dominates the plateau top. Lakes, ponds, and swamps are far more abundant than the outline map suggests. The topmost vesicular lavas are so pervious that a considerable part of the drainage is downward until more impervious horizons are reached, where it is deflected and eventually appears below the plateau rim. In spite of the fact that many streams, which accumulate sufficient volumes to be perennial sources of water for irrigation in the lower country, drain away from Boulder Mountain, only one flows over the rim of the mountain throughout the summer, according to Ranger Bentley. This unique stream is Pleasant Creek.

FIGURE 1. MILLER LAKE AT HEAD OF MILLER CREEK

FIGURE 2. BLIND LAKE BELOW NORTHEAST RIM

FIGURE 3. LANDSLIDE SLOPE

MARGINAL FEATURES OF BOULDER MOUNTAIN

FIGURE 1. WEST END OF BEEF MEADOWS

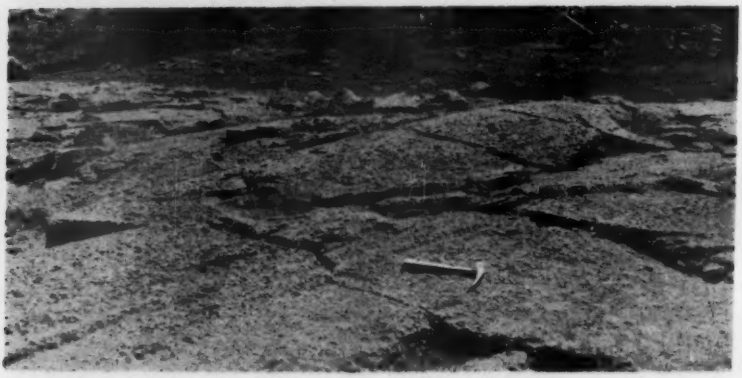

FIGURE 2. GLACIATED SURFACE OF VESICULAR BASALT

FIGURE 3. COOK LAKE

TOPOGRAPHIC FEATURES

CLIMATE AND VEGETATION

Differences in altitude have great effect upon climates throughout the plateau country (Gregory and Moore, 1931, p. 14). The length of growing season, temperature, precipitation, and rate of evaporation vary even in small areas. In the lower lands about the High Plateaus the growing season is two to three times as long as it is on top of the plateaus. Dixon (1935, p. 275) points out that all the lands below 7000 feet receive less than 8 inches of precipitation annually and are therefore deserts. Above this altitude the precipitation increases. Though there are no statistics for the top of Boulder Mountain and most of the country anywhere near it, Dixon (1935, p. 275) quotes Sampson to the effect that the lowest of three forest zones on the mountain flanks—the western yellow pine—receives an average of 19 inches; the aspen-Douglas fir zone above it from 25 to 29 inches; and the Engelmann spruce zone 25.9 inches.

Though the top of Boulder Mountain lies at what one would expect to be timber line, about 40 per cent of it is covered with heavy stands of Engelmann spruce. It is a dismal forest just now for the ravages of the spruce beetle have killed most of the trees. That such sturdy growths of Engelmann spruce have thrived at this altitude is due to the combination of a number of factors. Precipitation is conserved from rapid runoff by the flat tabular top of the mountain. Furthermore, the rate of evaporation is much lower than it would be about mountain peaks at the same altitude, owing to lower temperature and to less effective wind.

The vegetation reflects even the minor variations in the relief of the mountain top to an unexpected degree. The rounded knolls or sheep backs are spruce-covered, while the basins are either filled with lakes or with grass- and sedge-filled meadows. Though, as has been pointed out, the differences in altitude between the basins and the rounded ridges are slight, they are enough (Dixon, 1935, p. 299) to cause sufficient climatic differences to produce these two contrasted types of vegetation, which represent climax conditions. The snow lasts longer in the basins (good-sized drifts lay to the northeast of Bluebell Knoll in mid-August in 1938); the cold air drains from the ridges into them; the water table stands higher. Altogether, the rate of evaporation is less, and the growing season perceptibly shorter than on the ridges occupied by the spruce.

GLACIAL GEOLOGY

GENERAL STATEMENT

The features produced by glacial erosion and deposition may be divided into two groups: First, those on the mountain top, and second, those formed below the rim by the overflow of ice from the mountain top and

to a less extent by local accumulations in the lee or underneath the protection of the plateau rim.

THE MOUNTAIN TOP

The preglacial surface of Boulder Mountain must have been relatively flat. There were evidently no valleys sufficiently pronounced to collect the accumulating ice and so direct it as to cause the abrasion of well-defined U-shaped valleys. The expectable radial pattern from the erosional activity of an ideal plateau glacier or ice cap is difficult to detect. To be sure, where the ice flowed down preglacial channels near the margins, recognizable broad shallow grooves, separated by broad low rounded divides, are present. East and West Boulder Draws (Fig. 1) are the most persistent grooves and extend from the south rim well toward the center of the plateau top. A variety of features demonstrates that the greatest flow of ice was southward down these draws. The other major outlets extend inward from the plateau rim as imperfect and in places ill-defined grooves, which are lost in a maze of small knobs or basins, or the broad formless basins or meadows. Though frost action has been intense, glacier pavements with striated surfaces (Pl. 2, fig. 2) are common, and in a few places polished surfaces look as though they had just been waxed.

The broad divides which separate the major outlet grooves are themselves composed of low sheep backs and rock basins, many of which are filled with water. Naturally the largest glacial scour or rock basin lakes are found in the grooves, and the largest of all are in the lower parts of East and West Boulder Draws (Pl. 3, fig. 1).

It is the erosional forms rather than the depositional which give character to the relief on the top of Boulder Mountain. Though evidences of intense glacial abrasion are abundant, the expected depositional results of such action are not conspicuous. To be sure, there was not a great accumulation of preglacial soil on the top of Boulder Mountain, as may be seen near the ends of the great spurs, such as Chokecherry Point, which were not glaciated. Furthermore the imperfectly jointed basalts did not yield easily to quarrying or plucking. Altogether the depositional features both above and below the rim of the mountain are much less pronounced than would be expected.

The retreat of the ice front, after the ice cap had shrunk within the borders of the mountain or plateau rim, was not characterized by sufficiently long halts to allow the formation of well-defined recessional moraines. Only a few of the larger lakes in the shallow grooves are held in by morainal dams, and these are low and poorly defined. To be sure, the presence of such a maze of lakes with basins eroded from the vesicular

lavas is a reflection of the fact that in many places the basins are made impervious by till deposited directly in them or washed into them from surrounding slopes. The broad shallow meadows, many of the flatter knobs, and the gentle slopes about some of the steeper ones are covered with a thin veneer of till and rock fragments. Frost is even now a vigorous agency in adding to the litter of rock fragments, and during the waning of the ice cap the oscillating margin would have accentuated such effects by the plucking action of minor advances of the ice (von Engeln, 1930, p. 996).

FEATURES BELOW THE RIM

In spite of the steep gradients which characterized the outlet glaciers as they descended from the plateau rim, pronounced erosional features are not common. Everywhere about the rim, the shallow U-shaped depressions formed by these outlet glaciers are still hanging valleys. In many places one can stand at the heads of broad valleys which were clearly eroded by ice tongues from the plateau top and look up to the rim over which the ice must have flowed and detect little erosional effect. Postglacial weathering and the consequent recession of the rim rock have not appreciably modified these features anywhere. Figure 2 of Plate 3 is a photograph taken from the top of the plateau looking toward Pleasant Creek, which occupies a glacially eroded outlet valley, and Figure 3 of Plate 3 is taken from a position immediately below the rim of the same valley. This is a pronounced U-shaped outlet valley as such features are developed about the rim of Boulder Mountain.

Of all the places around the rim of Boulder Mountain over which the ice flowed down to lower levels, the most notable outpouring was toward the south. Apparently the ice accumulated in sufficient volume in these grooves to make a common ice apron or small piedmont below the rim. Though the ice continued as a stream down through the rock debris at least to 8950 feet, it did not scour deeply enough to penetrate through the accumulated rock slides, talus, and slumps to undisturbed bedrock below. Rock basin lakes are not found, and the retreat of the ice was not marked by sufficient halts to form conspicuous recessional moraines. Lakes due to morainal dams are therefore but shallow swamps (Pl. 4, fig. 1).

Though the outlet glaciers which descended the plateau rim elsewhere did not possess as great volume as those which drained southward, their retreats were more characteristically marked by halts and the development of recessional moraines. Fish Creek Lakes on the northeast side of the mountain are due to such dams (Pl. 4, fig. 2). Blind Lake (Pl. 1, fig. 2), which is the largest of all the lakes on top or around Boulder

Mountain, owes its existence chiefly to morainal dams. The two arms of this lake occupy shallow, moraine-flanked basins which were scooped out by two tongues of ice which flowed down from the plateau rim through two near-by depressions. The two tongues merged into a single stream of ice which pushed its way into and in part over a slump ridge. Ponds too small to be mapped are found in lower morainal bound steps below the large dam which holds the waters of Blind Lake. Donkey Lake Reservoirs below the north rim occupy positions analogous to those just described, and their origin is found in morainal dams. The natural dams have been raised about these and many other similarly formed lakes to create greater storage capacity for water.

Such barren zones as are conspicuous about Fish Creek Lakes (Pl. 4, fig. 2) are caused by lowering of the reservoir waters in the late summer months especially.

Though the major broad shallow grooves or "through" valleys are modified by recessional moraines in but few places, they are generally flanked by rugged lateral morainal ridges.

Apart from the larger outlet glaciers just described which were strong enough to plow their ways through the successive slumps or terracettes, the overflow from the ice cap on the plateau top was largely controlled by these landslide features. Of course the back slopes of these slumps in themselves constitute a series of basins, many of which are now filled with small lakes. Had there been no glaciation there would still have been a string of lakes underneath a considerable part of the plateau rim. Glaciation has, however, modified many of the landslide dams, and all the larger lakes are due chiefly to glacial action. Depending upon the direction and strength of the ice push into the landslides, two somewhat different results were produced. Either the ice tongue pushed futilely against a heavy landslide dam, making but little or no impression, or it spread laterally to form a sort of bulb glacier; or if the volume were sufficiently large and the ice tongue happened to push into the landslide at an angle, it then flowed along parallel to the landslide dam. Lakes of this sort, as well as the largest of the morainal dam lakes, are generally found from 500 to 700 feet below the east and north rims, reflecting the control induced by the wider bench found in these places, as pointed out earlier.

The larger fault slumps and detached parts of Boulder Mountain rim which characterize conditions below and beyond the western rim have exercised much more rigid control than elsewhere around the mountain. Had there been no glaciation there would still have been a more strongly developed string of lakes here than elsewhere underneath the plateau rim. Some of the lakes found here are caused solely by landslide

FIGURE 1. GLACIAL SCOUR LAKE IN EAST BOULDER DRAW

FIGURE 2. EASTWARD VIEW ACROSS PLEASANT CREEK MEADOWS

FIGURE 3. OUTLET OF PLEASANT CREEK

EROSIONAL FEATURES OF RIM

FIGURE 1. EAST FORK OF BOULDER CREEK FROM SOUTH RIM

FIGURE 2. FISH CREEK LAKES BELOW EAST RIM

GROOVES AND LAKES BELOW RIM

conditions, and others have been so slightly modified as to be most accurately described as landslide lakes. A conspicuous example is Cook Lake, which is a relatively long, narrow lake clearly reflecting the landslide character of its basin. The far side of the lake, that is the side away from the rim of Boulder Mountain, has two small bays. When one looks up to the rim of the plateau, he can see slight depressions which were occupied by weak tongues of ice which flowed down into the lake and pushed into the landslide dam on the far side of the basin just enough to make the margin of the lake irregular (Pl. 2, fig. 3).

Miller Lake (Pl. 1, fig. 1), 1½ miles south of Cook Lake, was produced by an ice tongue which flowed down from the plateau rim and was then forced to flow along parallel to a large slump ridge. A halt in the ice resulted in the formation of an end moraine which impounded the water to form the present Miller Lake. Most of the lakes along the western side of Boulder Mountain lie from 200 to 400 feet below the rim.

Though the recession of the cliff-bound rim of Boulder Mountain by great landslides or slumps occurred before the culmination of glacial conditions, various agencies of weathering, chiefly frost action, have been almost continuously at work. Such features as would be expected from the existence of perennial snowdrifts and even small local glaciers have therefore been obscured by postglacial accumulations of talus and other forms of rock debris.

CONCLUSIONS

Boulder Mountain presented practically ideal conditions for the development of the perfect ice cap or plateau glacier. Though ice must have accumulated first in such depressions as the broad meadows, the whole must soon have coalesced to form a common ice cap. Unhindered then by any nunatak barriers, the ice spread out in all directions until it spilled over the rim or became so thin that it ceased to advance as happened toward the extremities of only the larger, more extensive spurs such as that terminating in Chokecherry Point. In many places the overflow was too slight to produce lasting effects below the rim. In other places and particularly where directed by preglacial channels, the ice overflowed as ice tongues or outlet glaciers, descending from the plateau top in great ice falls or even as avalanche ice to form reconstructed glaciers where stopped by the first slump. Some of the ice tongues were then able to plow their way down through the rock debris to altitudes at least as low as 8950 feet. Others expended their energies in futile pushes against their landslide barriers or flowed along parallel to them.

The freshness of the glacial features indicates that they are to be associated with Wisconsin glaciation. Had there been ice accumulations earlier in the Pleistocene this last opulent ice cap would have obliterated them.

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SUBSIDENCE BY THRUSTING: THE DISCUSSION OF A HYPOTHETICAL FAULT

BY ANDREW C. LAWSON

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ABSTRACT

If a low-angle thrust cut through the sial into the dunite of the sima the region affected is uplifted by thickening of the crust. This concentration of mass puts the crust locally out of isostatic balance. The measure of uplift may be the same throughout a section transverse to the strike, but the excess load will vary with the density of the rocks intersected on the dip. If recovery of equilibrium be slow and the uplifted surface be subjected to erosion, there will be notable hypsometric contrasts in the profile of the region, when it again attains isostatic balance. The surface in that part of the section where the thickening is wholly in the dunite will be much lower than in the part where the thickening is wholly in the sial. It is suggested that in this principle may be found the explanation of certain large structural valleys like that of the Great Valley of California.

INTRODUCTION

If a thrust intersect the earth's crust the region above the fault is uplifted relatively to a constant datum. The uplift is a manifestation of concentration of mass, by thickening of the crust, which disturbs the

pre-existent isostatic balance. Equilibrium is re-established partly by erosional degradation of the uplifted surface and partly by sinking of the overloaded upper part of the crust into the dunite of the sima. But, although the original surface may have been level and the measure of uplift may be the same in all parts of the region above the fault, the surface, after recovery of isostatic balance, may present notable hypsometric contrasts.

ILLUSTRATIVE DIAGRAMS

This variation of surface altitude may be illustrated and explained by reference to the diagrams (Figs. 1 and 2) which represent a cross section of a portion of the crust traversed by a large thrust having a dip of 30 degrees. The uplift is supposed to be 10 km., such as would result from a horizontal dipward displacement of about 17.5 km. The original surface, before thrusting, is assumed to have been a peneplain at sea level. This peneplain presents a horizontal section through an old folded mountain range, into which granite had been abundantly injected. In the deformation which gave rise to the range both sial and basalt were involved, and so mixed that the mean specific gravity of the aggregate, including the granite, and of all parts of it above the dunite, is assumed to be 2.83. The specific gravity of the dunite is taken to be 3.3. The fault is discussed as if straight on its dip, although there is good reason to believe that many, if not all, low-angle thrusts curve to steeper dips in depth.

The uplifted region is divided into three zones, indicated on the diagrams as A, B, and C. In A the increase of mass occurs in the mixed aggregate in the upper part of the column. In B the increase of mass is due to increments of volume of both dunite and the mixed rock above it. In C the increment of volume, and therefore, of course, of mass, is wholly in the dunite. In all three columns the increase of volume is the same, and the uplift of the surface is the same; but the increase of mass is different. Since isostatic balance has to do with mass, independently of volume, the adjustment in the crust necessary to restore balance is quantitatively different in the three columns.

As will appear in the sequel, there are conditions of stress and consequent movement in the earth's crust antecedent to a large thrust, but these need not enter into this preliminary discussion. As soon as thrusting sets in, adjustment to reduce the excess load begins; and for this reason, and also because of erosion, the uplifted surface will never reach the altitude of 10 km. above sea level. The thrusting is probably a protracted and fitful process, and the relative rates of fault movement, erosion, and isostatic sinking are unknown. We may, however, discuss

the problem of the hypsometric result as if the surface had been uplifted 10 km. and then reduced to a level of isostatic equilibrium. Similarly, although erosion and sinking operate simultaneously, we may estimate

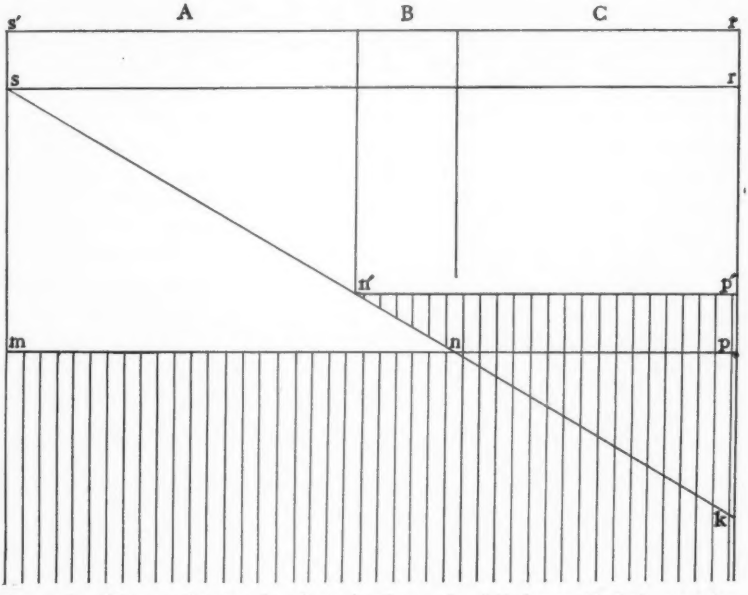

FIGURE 1.—*Diagram showing the effect of a thrust, sk, of 30-degree dip, before erosion and isostatic sinking.*

Surface, *sr*, is a peneplain at sea level, and *mnp* top of dunite before displacement at 46.4 km. below sea level. Heave of fault is 17.5 km. and raises the surface 10 km. to *s'r'*. In zone A thickening of crust, 10 km., is confined to mixed rock of specific gravity 2.83. In zone C same thickening occurs in dunite of specific gravity 3.3. In zone B thickening is partly in mixed rock and partly in dunite. In zone A top of dunite is not affected; in B and C it is raised 10 km. to position *n'p'*.

their effect separately, as if one had been finished before the other began.

Since the rates of erosional removal and sinking are unknown, there are various solutions of the problem, in accordance with the values which may be adopted for these rates. It is proposed here to present only one solution, the purpose being to illuminate the principle involved rather than to specify the details of its operation. This solution is arrived at by assuming that, from the initiation of the thrust till the final re-establishment of isostatic equilibrium, a mean thickness of 3 km. has been removed by erosion from the surface of the entire region, including the three zones A, B, and C, and that there is little departure from the mean anywhere.

If prior to the thrusting the region be in isostatic equilibrium, and without partial support from rigidity, the thickness of the mixed rock will be 46.4 km., and at this depth below sea level it will rest on the dunite.

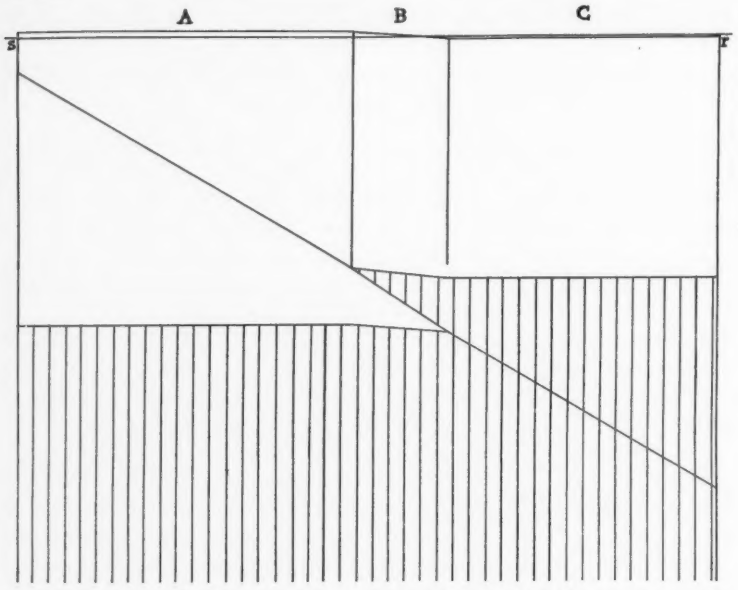

FIGURE 2.—*Diagram showing the effect of erosion and isostatic sinking on the profiles of columns A, B, and C as they appear in Figure 1.*

Line, *sr*, is sea level. Surface of A has been lowered to 1 km. above sea level, that of C to .4 km. below sea level, and that of B to an intermediate position. Top of dunite has been depressed 6 km. in A, 7.4 km. in C, and to between 6 km. and 7.4 km. in B. Thrust plane has been carried down 6 km. in A, 7.4 km. in C, and is broken or bent in B.

In zone A the excess load created by the thrust is 10 km. of specific gravity 2.83; and the surface, if there were neither erosion or sinking, would have an altitude of 10 km. Erosional removal reduces the excess to 7 km. To compensate this $\frac{2.83}{3.3}$ of $7 = 6.0$ km. of dunite must be eliminated from the lower part of the column, and this is effected by flowage into and mergence with the deeper dunite of the general body of the earth. The surface will thus be depressed to $7 - 6 = 1$ km. above sea level, and the whole column will be in isostatic balance. The net effect has been to raise the surface 1 km.

In zone C the excess load due to the thrust is 10 km. of specific gravity 3.3, and this by erosion becomes in terms of mass 3.3 x 10

$-$ 2.83 x 3 = 24.51. To compensate the excess the lower part of the column must lose $\frac{24.52}{3.3}$ = 7.4 km. of dunite by incorporation into the general body of deeper dunite. The surface is lowered to 7.4 $-$ 7 = .4 km. below sea level and is 1.4 km. lower than the surface of A.

In zone B the gravimetric relations on one side are the same as in A and on the other the same as in C. It is a gradational zone, and, when isostatic balance is finally attained, the surface will descend from the altitude of A to that of C by either flexure or faulting.

For given widths of the three columns the total quantity of dunite eliminated from their lower parts in the course of isostatic adjustment may be readily estimated. Thus, if the widths be: A = 62 km., C = 50 km., and B = 17.5 km., which are the proportions of the diagrams, then, for every kilometer measured along the strike of the thrust, there passes out from beneath A 62 $\times$ 6 = 372 cubic km., from beneath B 17.5 $\times$ 6.7 = 117.25 cubic km., and from beneath C 50 $\times$ 7.4 = 370 cubic km. of dunite. For the whole belt affected, the total quantity of dunite forced into the depths is 859.25 cubic km. for every kilometer of the thrust, measured on its strike.

MOUNTAIN ARCS OF THE PACIFIC COAST OF NORTH AMERICA

The mountain chains of the west coast of North America, south of Alaska, are disposed in three approximately circular arcs convex to the Pacific Ocean. The most northerly arc comprises the Olympic Mountains, the Vancouver Island chain, and that of the Queen Charlotte Islands. It may be referred to as the Vancouver arc. The second comprises the Coast Ranges of Oregon and California, extending from the latitude of Aberdeen, Washington, to about Lat. 32° N., and may be called the California arc. The third or most southerly arc comprises the great mountain ridge of Lower California and the Sierra Madre del Sur, from Cape Corrientes to Salina Cruz. It is here called the Mexican arc. These three arcs are orographically similar to the insular arcs of the Asiatic side of the Pacific Ocean and to the Aleutian arc.

The Vancouver arc has a radius of about 765 miles. On its concave side lie the depressions of Puget Sound, the Gulf of Georgia, Queen Charlotte Sound, and Hecate Strait. The California arc has a radius of about 1155 miles. On its concave side lie the depressions of Upper Puget Sound, the Willamette Valley, the Great Valley of California, and Salton Sea. The Mexican arc extends from about the northern boundary of Mexico to the Gulf of Tehuantepec with a radius of 1435 miles. In its concavity is the Gulf of California and its extension as

a land valley between the Sierra Madre del Sur and the southwestern front of the Plateau Central of Mexico. In none of these three arcuate chains is the structure of the mountains parallel with the curvature of the arcs. The strike of the axes of folding and of the faults is prevailingly discordant to the plan of the arcs. The mountain-making movement, which gave them their internal structural features, antedates the crescentic uplift.

The Mexican arc has a well-defined foredeep with two maxima of depression, one having a depth of 5120 meters and the other of 4866 meters. In this respect the Mexican arc is more strictly analogous to the insular arcs of the other side of the Pacific than are the California and Vancouver arcs, which have no notable foredeeps.

If, following Lake (1931), the probability be accepted as a reasonable hypothesis that the outline of the Himalayan arc, the Aleutian arc, and numerous other arcs represent, in every case, the trace of the intersection of a great low-angle thrust with the spheroid of the earth, then the same hypothesis may be adopted for the Vancouver, California, and Mexican arcs. It is proposed here to examine this hypothesis, particularly to inquire into its consequences as affecting the profile of the earth's surface on the landward side of one of the arcs.

The radius of an arc gives us immediately the approximate angle of dip of the thrust on which the crescentic block rides. The Vancouver arc with a radius of 765 miles is the trace of a fault which dips 11° 10′ to the northeast. The California arc with a radius of 1155 miles indicates that the Coast Ranges of California ride on a thrust having an eastward dip of 17 degrees; and the dip of the thrust which determines the Mexican arc is 21° 18′. For the sake of comparison it may be stated that the Aleutian arc has a radius of about 850 miles and an inferred dip of the underlying thrust of about 12 degrees; and the Himalayan arc has a radius of 1022 miles and a thrust dip of 15 degrees.

It is unnecessary here to go into the question of the origin of major compressive stresses in the earth's crust. Many great thrusts and many folded mountain ranges attest to the reality of such stresses. The conditions which determine the location and the dip of low-angle thrusts, when compressive stress exceeds the strength of the crust, may, however, be briefly discussed.

LOCI OF LOW-ANGLE THRUSTS

In an interesting and valuable paper on low angle-faulting, Chamberlin (1918, p. 1-44) has discussed the conditions under which low-

angle thrusts are developed in the earth's crust by compressive stress. When rocks break under compression which develops no rotational strain, the fractures make an angle of about 45 degrees with the direction of the principal stress. When, however, the configuration of the part of the crust subject to excessive compression, as revealed in its surface profile, is such that the stress gives rise to rotational strain, the fracture becomes partially a shear at angles lower than 45 degrees with the direction of stress. This is well illustrated when a block of brittle material, such as cold paraffin, is placed in a vise, with a larger area of support on one side than on the other, and caused to break, as in the diagram (Fig. 3). When the block A fails, the rupture begins at *b* and is propagated across the block to *c*. At *b* the conditions are those of almost pure shear, and the initial break is a nearly horizontal crack. The crack, as it develops, bends down till it reaches 45 degrees with the horizontal and continues across the block at that angle. The conditions exemplified in this experiment are reproduced to some extent on a great scale when the surface of the crust which fails under compression is one of high relief. Thus the base of a high range, under compression, might be expected to become the locus of a shear, or thrust, when the stress exceeds the shearing strength of the rock. The great thrust plane which passes under the Himalayas at an angle of about 12 to 15 degrees with the horizon is a case in point. The lowness of the angle was doubtless determined by the rotational strain caused by the high free front of the range, as compressional stress approached the limiting strength of the rocks. In one respect a high range like the Himalayas differs from the paraffin experiment. As the thrust under the range develops, the mountain mass above the thrust rides higher and higher. This both intensifies the rotational strain and carries it farther back from the front; so that the tendency to break by shear also extends farther and farther back. Under these conditions smallness of the angle of rupture would extend far under the rising mountain. Many other mountain fronts present low-angle thrusts at their base. Indeed, these fronts appear to be the favored situations for such ruptures of the crust. It would be difficult to imagine the initiation and development of a low-angle thrust traversing the great peneplain of the Canadian shield, since there is little in its relief to suggest the possibility of rotational strain, as the result of compression. This does not of course preclude the existence of great thrusts in that vast region. It was once a region of high relief, and any low-angle thrusts that may be found there could well have been developed when high mountain fronts dominated the landscape. If low-angle

thrusts, at the time of their formation, have their fault traces prevailingly and characteristically at the base of mountain fronts, then one is tempted to say that, where they are found today in regions of low relief, their occurrence is significant of the erosional removal of

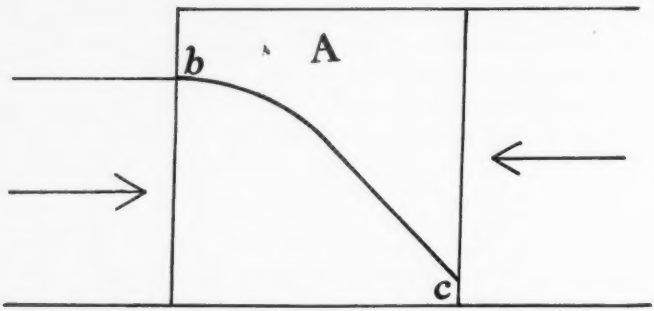

FIGURE 3.—*Diagram showing the effect of asymmetric pressure on a prism of cold paraffin held in a vise.*

A prism of cold paraffin, A, is placed in jaws of a vise so that part of left side is free, while, on the right, pressure applies to whole surface. When compressed to point of failure break occurs at b, close to bottom of free surface, and makes a small angle with direction of stress. It then curves to 45 degrees with direction of stress and so continues across prism to *c*.

the mountains and that we might use such thrusts as a key to the mapping of paleogeographic relief.

Another general situation where rotational strain would be developed by compressive stress is at the base of subaqueous slopes along continental margins. The writer has indicated in another paper (Lawson, 1938) that the continental shelf is the surface of an embankment of great depth, sheared down against the side of the continent. The embankment may be as much as 8 km. thick, and, since it consists of sediments of little or no strength, supported on the landward side by a steep rock-slope, or wall, produced by shearing, the conditions are ideal for the development of rotational strain under adequate compressive stress. It should be expected, therefore, that the base of this wall, beneath the embankment, would be a favored locus of low-angle thrusts. By the operation of such thrusts large fractions of the embankment would be carried under the continental margins, and, insofar as this is the case, there would be a pronounced tendency for the outer slopes of the embankment to remain steep.

The only instances of thrusts in this subaqueous situation which can be cited are the hypothetical thrusts which underlie the great insular

arcs, such as the Aleutian and others, of the Asiatic Coast (Lake, 1931; Lawson, 1932). It is difficult to explain these arcs as other than uplifts on low-angle thrusts from the Pacific under the continental margin. Their configuration appears to be determined by the trace of the intersection of a flat fault with the spheroid of the earth. The trace itself is probably in the ocean, at the base of the steep coastal slope. For the California arc it is necessary to recognize at least the probability of a great thrust upon which the mountain crescent rides. The trace of this fault should be near the bottom of the subaqueous slope beneath the embankment of the continental shelf. In that situation would occur the first rupture under excessive compression, and there rotational strain would be most effective for low-angle shear.

THE CALIFORNIA ARC

CONDITIONS ANTECEDENT TO THRUSTING

Since the purpose of this paper is to ascertain whether a low-angle landward-dipping thrust passing into the dunite under the region of the present Great Valley could account for the depression of the latter, it is necessary to inquire into the conditions which prevailed in the region at the initiation of the thrust. The thickness of the sedimentary deposits resting on the sunken floor of the Great Valley has been estimated to be 4 km. in a section through Mount Whitney transverse to the trend of the Sierra Nevada. Vaughn (Lawson, 1936, p. 1699) has found a depth of 7 km. for a part of this depressed valley floor. But this is probably a local maximum, and, considering the valley as a whole, the mean depth of fill, along its axis, may be taken at 4 km. The marine and alluvial sediments of the fill rest on the worn (peneplained) surface of a complex of granodiorite and metamorphics, the mean specific gravity of which is taken at 2.83. The specific gravity of the sediments is probably about 2.4. On these assumptions the thickness of the mixed rock of specific gravity 2.83 may be readily found by equating the column under the valley with the standard oceanic column. If x be the thickness of the mixed rock, then, the altitude of the surface being about .1 km., $2.4 \times 4.1 + 2.83x + 3.3\ (46.4 - 4 - x) = 2.83 \times 46.4$; whence $x = 39.25$ km. This is the thickness of the mixed rock under the valley necessary to maintain isostatic balance. It was also the thickness of the mixed rock when its surface, by erosion and depression, reached sea level and began to be covered with deposits, marine and alluvial, which now underlie the valley floor.

If in fact the Coast Ranges ride on a low-angle thrust, which intersects the top of the dunite beneath the eastern border of the moun-

tains and so causes the depression of the Great Valley, certain conditions must obtain. The dip of the hypothetical thrust is 17 degrees and its outcrop is not known anywhere above sea level. The most probable position for the outcrop is at the base of the steep submarine coastal slope, which lies beneath the embankment of the continental shelf. It is supposed by the writer to be located on the buried slope at a depth which, measured vertically below the shore line, would be 4.5 km. The thrust on the upward projection of its dip would thus intersect the sea surface at a distance of 14.7 km. from the shore. The width of the Coast Ranges at sea level is taken as 122 km. From these data it is found that the thrust should intersect the vertical below the eastern border of the mountains at a depth of 41.8 km. To meet the requirements of the general hypothesis, this is the depth below sea level at which the thrust should cut the boundary between the mixed rock of specific gravity 2.83 and the underlying dunite.

SUPPORT FROM RIGIDITY BEFORE FAILURE

In our consideration of the problem, we may start with a peneplain at sea level as the top surface of a body of mixed rock 46.4 km. thick. The column is then in isostatic balance with the standard oceanic column. The first effect of a compressive stress adequate to deform the earth's crust would be the upward arching of the latter. This bowing of the crust may be very broad and low, but it involves two conditions of importance; (1) Rotational strain, and (2) the rise of the dunite below the arch. The addition of the dunite to the column increases its weight in excess of that which is normally supported by isostatic balance. This excess load is sustained by the rigidity of the crust. But as soon as arching sets in the surface is lifted into the zone of erosion, and the excess load is reduced by degradation progressively with the uplift. It is probable, from a general point of view, that arching of the crust is a precedent condition to the development of every great thrust. When the thrust becomes operative and the compressive stress is discharged, the support by rigidity ceases, and the hypsometric position of the column is again wholly dependent upon isostatic balance. Even if erosion before failure removes a thickness of the mixed rock equal to the amount of the uplift, there will have been added to the bottom of the column an equivalent thickness of dunite; and, although the surface may be again at sea level, there will still be an excess load to be supported by rigidity. The measure of the excess will then be the amount of the uplift multiplied by $(3.3 - 2.83)$ or .47. For an arch uplift of 4 km., the excess would be only 1.4 per cent of the total gravitative

stress of the column down to the 46.4 km. level. The other 98.6 per cent is supported isostatically.

The erosional removal from the surface thus lifted may be any thickness up to the measure of the uplift, depending upon the relative rate of uplift to that of erosion. It will be convenient to regard the uplift as relatively very slow, so that all that was raised into the zone of erosion was removed before the failure which initiated the thrust. During erosion the crust was being weakened, and failure may have ensued before the limiting value for erosional removal, here adopted, was reached. The difference would, however, have been merely arithmetical and would not essentially affect the problem.

The recognition of the uplift by arching, as a precedent condition to failure of the crust by compression, and the pre-thrust erosion which the uplift determines, while the excess load is sustained by rigidity, explains how the thickness of the mixed rock may have been only 41.8 km. instead of 46.4 km., at the time when the thrust sliced the contact of mixed rock and dunite.

EFFECT OF THE THRUST

When failure occurred the thrust movement thickened the crust by, say, 16 km., corresponding to a horizontal dipward shift or heave of 52.3 km. As before, this thickening of the crust divides the region into three zones: a westerly one (A) in which the thickening occurs wholly in the mixed rock; an easterly one (C) in which the increment of volume is confined to the dunite; and an intermediate zone (B) in which the increment is partly mixed rock and partly dunite.

In zone C, whatever the uplift by arching may have been, the total erosion, both during the maintenance of the arch uplift and after the thrust uplift, reduced the thickness of the mixed rock from 46.4 km. to 39.25 km. (the present thickness under the valley). The total erosional removal of the mixed rock from the surface of the column is thus $46.4 - 39.25 = 7.15$ km. The thickness of the dunite down to the 46.4 km. level, when the column sank to the position of isostatic balance, may be found from the following equation, in which x is the measure required:

$$2.83 \times 39.25 + 3.3\,x = 46.4 \times 2.83$$

whence $x = 6.13$ km.

The total thickness of the column down to the 46.4 km. level is thus $39.25 + 6.13 = 45.38$; and the surface of the mixed rock is $46.4 - 45.38 = 1.02$ km. below sea level. The addition of 4.1 km. of valley fill of specific gravity 2.4 depressed this surface to 4.0 km. below sea level, and the valley floor was raised by the fill to $4.1 - 4.0 = .1$ km. above sea level, which is its present altitude.

In zone A the crust participated in the same uplift by arching, and, on the failure of the arch, the same uplift by thrusting as in C. The depth of the bottom of the mixed rock when thrusting set in was the same, *i. e.*, 41.8 km. below sea level. The present surface is about 1 km. above sea level. For isostatic balance at this altitude the thickness of the mixed rock must be 53.42 km., and its bottom is 52.42 km. below sea level. The total erosional removal both during the arch uplift and after the thrust was $46.4 + 16 - 53.42 = 9$ km., as compared with 7.15 km. in zone C. The difference in altitude between the surface of the mixed rock in A and in C, before the latter was loaded by valley fill, is $1 + 1.02 = 2.02$ km.

In zone B the load added by thrusting is, on its west side, the same as in A, and on its east side the same as in C. It is therefore a relatively narrow zone gradational as to altitude between A and C. The hypsometric relations of the three surfaces are similar to those shown in figure 2.

MEASURE OF SINKING

In zone A the measure of the sinking to the position of balance is that of the thickening by the thrust less the erosional removal and less the present altitude of the surface. The mixed rock just prior to the thrust was 41.8 km. thick. The effect of the thrust was to add 16 km. to this, making the total thickness 57.8 km. The present thickness, the surface having an altitude of 1 km., is 53.42 km. The difference—4.38 km.—is the thickness of the prism lost by erosion. The column, therefore, in its recovery of isostatic balance has sunk $16 - 4.38 - 1 = 10.62$ km. This vertical movement of the crustal column in zone A is shared by the region to the west of the outcrop of the thrust in the immediate vicinity of the latter; but the sinking diminishes rapidly in amount seaward, since the load imposed by the thrust is reduced to zero a short distance from the coast. The offshore sinking contributes to the accommodation of the thick embankment of the continental shelf.

In zone C the dunite was thickened also 16 km., and the surface lifted a corresponding amount, for so far to the eastward as the dip of the thrust continued at a uniform angle of 17 degrees. It is probable, however, that the angle of dip increased in depth, with a diminishing horizontal component of displacement, and that the increasing vertical component was taken up by the underthrust block plunging down into, and merging with, the deeper dunite by plastic flow. In the region where this occurred the uplift of the surface and the load added to the column above the thrust became fading quanti-

ties; so that the eastern boundary of C is indefinite. For any part of C across which the thrust maintained a uniform dip of 17 degrees, the total erosional removal, both during the arch uplift and after the thrust, was 7.15 km. The removal during the arch uplift was 4.6 km., and that after the thrust was $7.15 - 4.6 = 2.55$ km. The sinking of the column in the recovery of balance after the thrust was $16 - 2.55 + 1.02 = 14.47$ km. The sinking of the crust in this part of C was thus 3.85 km. more than in A.

The sinking of A and C would carry with them the thrust itself; and, since the sinking is differential, the thrust must be dislocated by a large normal fault or flexure in zone B.

CONCLUSION

Accepting Lake's (1931) suggestion that the configuration, in plan, of arcuate mountains is the expression of the intersection of low-angle thrusts with the spheroid of the earth, the writer exploits this hypothesis by applying it to the California arc. It is assumed: (1) That the Coast Ranges ride on a thrust which, when functional, had an eastward dip of 17 degrees, an outcrop on the coastal slope 4.5 km. below the shore line, beneath the embankment of the continental shelf, and an intersection with the top of the dunite 41.8 km. below sea level, at the eastern border of the present mountains, (2) that an antecedent condition of thrusting was a low arching of the region, during which the excess crustal load so created was supported by rigidity, and (3) that the horizontal dipward displacement on the fault was about 52 km., whereby the crust was thickened, and the part above the thrust raised, 16 km. These assumptions provide a mechanism which, after the recovery of isostatic balance, would have uplifted the Coast Ranges 1 km. and simultaneously depressed the Great Valley 1.02 km.

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FORAMINIFERA OF SUBMARINE CORES FROM THE CONTINENTAL SLOPE

BY FRED B PHLEGER, JR.

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ABSTRACT

The foraminiferal fauna in more than 35 submarine cores, collected by H. C. Stetson from the continental slope of the western North Atlantic, have been examined to determine the areal and vertical extent of present and previous assemblages. Below the present fauna, recorded at the top of the cores, there is a widely distributed fauna of Arctic to sub-Arctic aspect not now living in this area. This fauna is similar to the one reported from the Georges Bank canyons and from a core in this area, and is identified by Cushman as Pleistocene. This Pleistocene fauna is probably of Wisconsin age, since it lies directly beneath the present fauna. At the western edge of the basin of the North Atlantic ocean, beyond the continental slope, two Arctic faunas have been recognized below the Recent assemblage and are separated by a pelagic warm-water fauna typical of the present Gulf Stream region. This may represent two Pleistocene stages or it may indicate separate maxima of the last stage.

In a few cores a foraminiferal fauna is recorded a short distance beneath the surface in which pelagic types characteristic of warm surface water are considerably more abundant than in the present-day assemblage. This suggests a possibility of a postglacial shift in warm surface water areas.

New information concerning distribution suggests that water temperature may be the most important regulating factor in the occurrence of many Foraminifera.

INTRODUCTION

GENERAL STATEMENT

Recently, while examining various submarine cores for Foraminifera, Cushman observed an Arctic foraminiferal fauna at a short distance from the top of some of the cores taken from the Georges Bank canyons, in a core about 100 miles southeast of New York City, and in the cores collected by Piggot across the North Atlantic at the position of the cable crossing. In all these occurrences the implication has been that the Arctic fauna (or faunas) represents accumulation during the Pleistocene glaciation.

It has seemed desirable to check these discoveries with further submarine exploration. Accordingly the writer was given the opportunity of studying the Foraminifera of several cores collected by H. C. Stetson of the Woods Hole Oceanographic Institution during 1938 and subsequent seasons. All the present cores, taken with the coring gun developed by Piggot, attain a maximum length of 10 feet (3 meters); the average length is about 7 feet (2 meters).

The main purpose of this study has been to ascertain whether an Arctic foraminiferal fauna or faunas occurs in cores taken some distance south of most previous ones, and, if so, the areal distribution. A study of the sediments is being undertaken by Stetson. The present paper is concerned only with the Foraminifera in the cores and their direct bearing on Recent and past conditions in this area of the Atlantic. A study of this type should have an important bearing upon the interpretation of marine conditions during the time that such an Arctic fauna was deposited. For the present report all but one core are from a section of the continental slope of the western North Atlantic. The collected material

is still considered incomplete, even for the continental slope. Inasmuch as this and related researches will continue for some time, it is considered timely to present a summary of the present contributions. Before any far-reaching conclusions can be established it will be necessary to continue the coring and faunal study of the continental slope and the ocean basin.

ACKNOWLEDGMENTS

A considerable part of this work was done at the Woods Hole Oceanographic Institution during the summer of 1937, and the writer is grateful to that institution for facilities and other aid in research. The writer is particularly grateful to Henry C. Stetson who has generously placed the core faunal material at his disposal and has been most helpful in other ways; and to Dr. Joseph A. Cushman for the use of his laboratory and equipment and for many useful suggestions. Many of the faunal data have been discussed at length with Miss Frances Parker, who is conducting a closely allied research. The generosity of the Geological Society of America in awarding a grant from the Penrose Bequest has made continuation of this work possible.

LOCATIONS OF CORES

All the cores here discussed came from the continental slope, from a position east of New Jersey to east of Chesapeake Bay (Fig. 1). They are in three groups: The 1936 cores run in a line south of Cape Cod, beginning at about 40° N. Lat. or about 100 miles due south of Martha's Vineyard. Thirteen cores were collected from this traverse, but only 10 are here discussed. One group of the 1938 cores, 11 in number, is more or less parallel to the coast line at a position east and slightly north of Delaware Bay. The third group, consisting of 9 cores, is east and slightly north of Chesapeake Bay. The geographic position of each core, as recorded in the deck log of the "Atlantis," is given in Table 1.

The depth of the cores ranges from slightly beyond the break in slope at 215 meters to the eastern part of the ocean basin at 3900 meters. This is a complete traverse of the continental slope, and this range in depth is shown only in the more northerly line. The southerly group ranges in depth from 402 to 1990 meters and represents primarily the upper two-thirds of the slope.

An attempt was made in 1938 to collect in view of the rugged submarine topography shown on recent maps compiled by Veatch and Smith (1939). This was done largely to examine the comparative rates of deposition, if possible, in the valleys and on the divides of the canyons there present. At Veatch's suggestion a series of traverses were made across certain of the valleys which he had contoured. As a result the cores are placed

parallel to the coast line and are quite variable in depth. In some cases it was difficult to locate exact positions in relation to the submarine topography due to the difficulty of obtaining an exact position at sea by ordinary methods. This probably accounts for the variations in depth

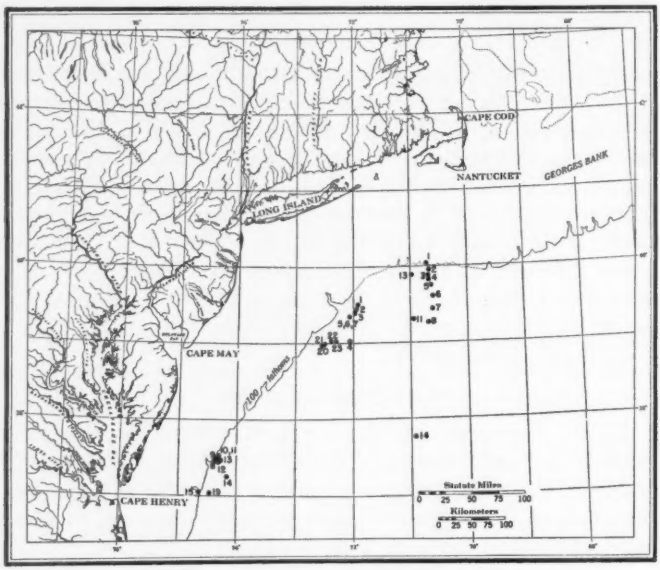

FIGURE 1.—*Map showing locations of submarine cores*

The smaller numbers are the 1938 cores. (Base map by courtesy of the United States Coast and Geodetic Survey.)

observed between the depths here given and those shown by the topography if the positions are plotted on Veatch's maps.

METHOD OF STUDY

Cushman, Henbest, and Lohman (1937) have commented upon the possibilities of the mixing of the sediments, and consequently the microfaunas, in the coring of the bottom. It is obviously of importance to know whether true vertical relationships between samples are shown. They have concluded that the only zone of mixing occurs around the outer surface of the cores because none or only a few of the species present in the bottom sample of their core occur at the top.

In the present writer's experience the above conclusions are correct and are supported by the following observations: (1) In cores in which there

is a succession of layers of sediments of different colors or texture, a thin film of the lower layers coats the outside of the core at the position of the upper layers. This is particularly noticeable in core 21-38 in which white Eocene material underlies a gray mud; a thin layer of the white

TABLE 1.—*Locations and depths of cores*

Core	N. Lat.	W. Long.	Depth	Length of core
1	40° 1′	70° 42′	215 meters	85 cms.
2	39° 57′	70° 41′	395 meters	289 cms.
3	39° 53′	70° 41′	647 meters	289 cms.
4	39° 50′	70° 41′	1050 meters	244 cms.
5	39° 45′	70° 39′	1954 meters	91 cms.
6	39° 36′	70° 36′	2250 meters	106 cms.
7	39° 26′	70° 37′	2579 meters	225 cms.
8	39° 15′	70° 42′	2740 meters	109 cms.
11	39° 18′	70° 57′	2660 meters	194 cms.
13	39° 53′	70° 58′	556 meters	190 cms.
14	37° 42′	70° 53′	3900 meters	299 cms.
1-38	39° 30′	71° 53′	1097 meters	244 cms.
2-38	39° 27′	71° 56′	1325 meters	132 cms.
3-38	39° 24′	71° 57′	1025 meters	264 cms.
4-38	39° 02′	72° 01.5′	1042 meters	115 cms.
5-38	39° 21.5′	72° 02′	1160 meters	149 cms.
6-38	39° 20.5′	72° 03.5′	1710 meters	175 cms.
7-38	39° 19′	72° 05′	1125 meters	156 cms.
8-38	39° 28.5′	74° 23′	660 meters	110 cms.
9-38	37° 27′	74° 24′	542 meters	143 cms.
10-38	37° 25′	74° 27′	878 meters	187 cms.
11-38	37° 24′	74° 28′	402 meters	138 cms.
12-38	37° 21′	74° 21′	1450 meters	147 cms.
13-38	37° 22′	74° 20′	1080 meters	124 cms.
14-38	37° 17′	74° 09′	1990 meters	148 cms.
15-38	37° 03.5′	74° 38′	610 meters	183 cms.
19-38	37° 02.2′	74° 29′	1430 meters	175 cms.
20-38	38° 57.5′	72° 30′	1455 meters	208 cms.
21-38	38° 58′	72° 28.5′	1565 meters	157 cms.
22-38	39° 02′	72° 21.5′	860 meters	171 cms.
23-38	39° 01.5′	72° 17′	1665 meters	235 cms.

sediment coats the darker material above for a few inches vertically. The thickness of this outside veneer is about one-sixteenth of an inch. (2) There is no disturbance of thin layers where they can be observed. In some cases there is a slight drag on the outside of the cores, but this is confined to the outer fraction of an inch.

In sampling, every reasonable precaution has been taken to prevent contamination within and between cores. As the cores come out of the gun they are sealed in a brass tube the diameter and length of the core itself (Piggot, 1936). This is carefully split with several sheets of iron which have been sharpened on one edge, and two equal halves are obtained. After one of these cutting tools has been used it is thoroughly washed to remove any mud or sand. The only mixing which might occur

is a horizontal one, and some of the veneer of material coating the outside may be spread on the flat surface of each half.

In taking samples for study of the Foraminifera only a quarter section of a core has been used, and of this a piece has been taken up to a maximum length of 10 cms. One-eighth to three-sixteenths of an inch has been carefully removed with a knife from all the outer surfaces of each sample. With these precautions the sample obtained is considered accurate. The vertical positions of the samples within the cores have been determined, where possible, on variations of lithology. In those cores which exhibit no apparent change in lithology the samples were taken at top, middle, and bottom.

THE FORAMINIFERAL FAUNA

GENERAL STATEMENT

It is not the purpose of this paper to deal in detail with the areal distribution of the foraminiferal fauna of the continental slope. Considerable work of this kind has been done by Cushman (1918-1931) and is being continued by Cushman and by Miss Frances Parker at the Woods Hole Oceanographic institution. In the accompanying faunal charts (Tables 2, 3) are listed species which occur in most or a large number of the core samples. This list represents less than one-third of the total number of species observed in the entire suite of samples. All those omitted are so relatively rare that it has not been considered necessary to include them in this paper. From plotting of the data of their occurrence it cannot be shown at the present time that they have any significance in the problems at hand. No attempt is made, moreover, to describe in detail the various species listed. In some cases brief distinguishing features are mentioned in the important forms, and remarks on distribution are included which seem pertinent to the problems. Only those species are figured which are either diagnostic in this type of study or are so prevalent over a large area that they cannot be ignored. All identifications have been verified at the Cushman Laboratory for Foraminiferal Research.

THE RECENT FORAMINIFERAL FAUNA

The Recent foraminiferal fauna occurs in the bottom sediments deposited since the Pleistocene and is present in the top of all the cores, extending downward for a varying distance. The average sample from the continental slope sediments is characterized by an abundance of individuals of typically pelagic forms, particularly of the families Globigerinidae and Globorotaliidae. Other types occur in abundance but are not so widespread as these; the Orbulininae are widespread and fairly abundant but rarely constitute a very large percentage of any sample.

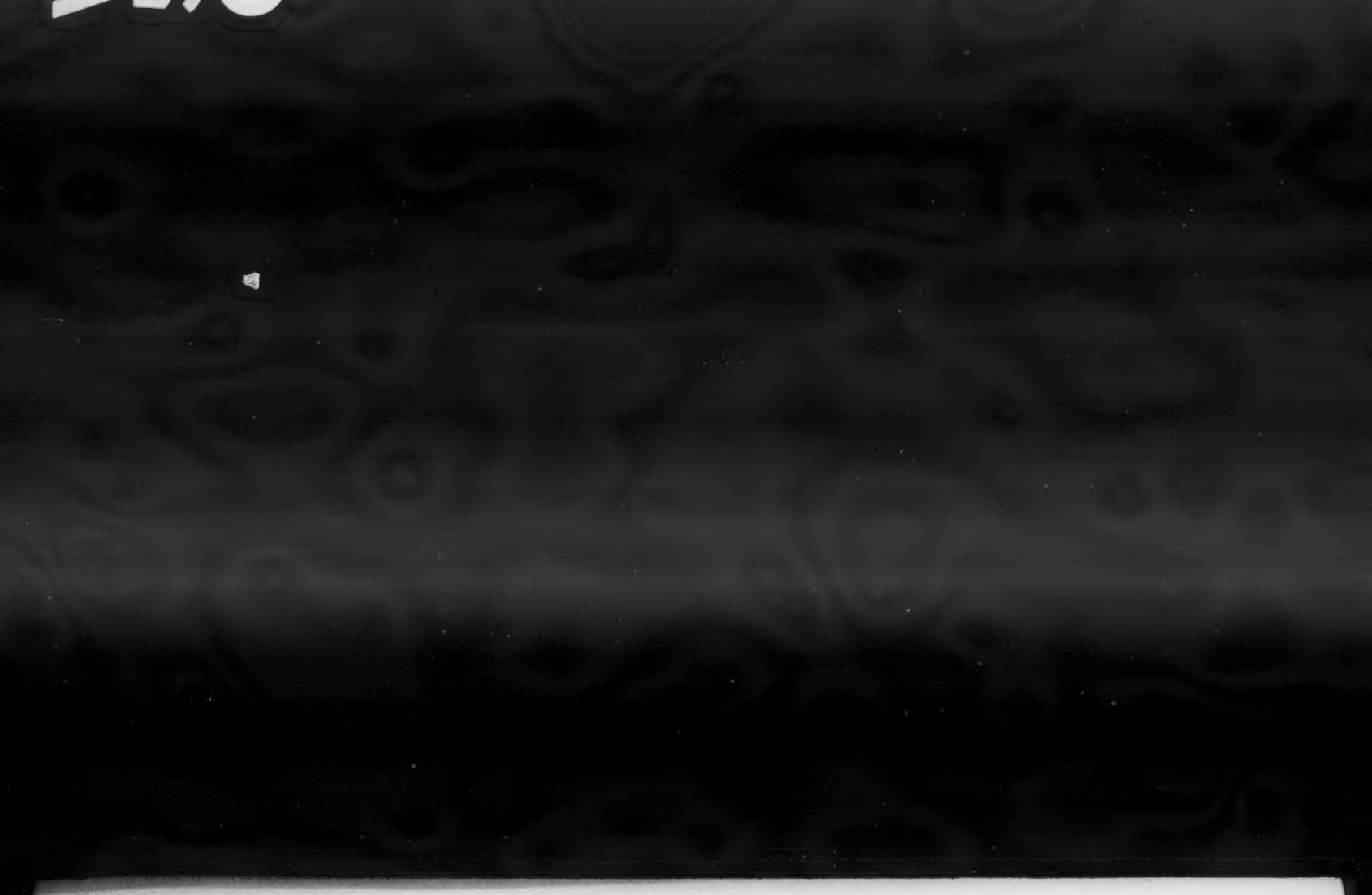

TABLE 2.—*Distribution of Fo*

CORE	1		2				3					4				5		6	
Sample	1	2	1	2	3	6	1	2	3	4	9	1	2	3	7	1	2	1	2
Saccamina sphaerica			R	R			R					C							
Proteonina difflugiformis							R					C							
Eggerella																			
Textularia												R							
Listerella occidentalis	C			C														R	
L. communis	R		A				R												
Karreriella bradyi							R	R				C	C						
Quinqueloculina seminulum								R	R	A	R		R						
Q. sp.		C																	
Triloculina tricarinata					R								R	R				R	
Pyrgo subsphaerica					C	R		R	R	R	R		R	R		R		R	
Other pyrgos				R															
Robulus	C	C	R												R	R	R		
Marginulina bachei	C	R	R																
Lagena			R	R	R	R		C	R	R		R	R	R					
Nonion cf. grateloupi			R		A	C	R	A	A	C	C	C	R	R	C		R		
N. labradoricum			C		C	C	R	A	R	A	C	R	A	A	C		C		
N. pompiloides	R	C		R															
Elphidium sp.			C				R	R		C	R	R	R		R		A	R	
E. advenum var. *margaritaceum*		A	R	R	A	A	R	A	A	A	R		A	A	R	R	R	C	A
Bulimina marginata	A	A				R			C					R	R				
B. aculeata			A	R	R		A	A	R			A	A			C	C		
B. cf. affinis	A		C	A			R	A	R	R	R		A	C	C		C	R	R
B. inflata				R	R												R		
Uvigerina		R	C		C		A	C				A	A	R	R	R	R	A	R
Angulogerina angulosa	A	A	R			R										R	A		
A. sp. 1							A	R	R			R							
Buliminella elegans var. *azilis*			A	A	A	A	C	R	C	C	R	R	C	A	C	C	R	R	R
Virgulina schreibersiana	A																		
V. squammosa			R	R			R	C	C	R			R	R					
Bolivina subaenariensis	C	R					R		R					C					
B. subspiniscens												R							
B. sp. 1	A							R	R	R		R	R						
Gyroidina soldanii	A			R			C	R				C	C	R	R			R	R
Rotalia cf. beccari																			
Eponides				A								R		R		R		R	R
Cassidulina laevigata		A	C		A	A	R	A	A	A	A		A	A	A	R	A		C
C. subglobosa		A	R		C	A		C	R	A	A			A	C				
Cassidulinoides bradyi	C																		
Globigerina bulloides	A	C	A	A	C	A	A	A	A	C	C	A	A	A	C	C	C	A	A
G. inflata	A	C	A	A	C	R	A	A	A	R	R	A	A	A	R	C	A	A	A
G. dubia	A	R		C	R		A	A			R	A	C		R	C	R	A	A
G. pachyderma			R		A	A		C	A	A	A		A	A	A		A	C	C
Globigerinoides rubra			R	A				R	R			R	R					C	R
G. conglobata	C		A	A			C	C	R			C				C		A	C
G. sacculifera		R	R													C		C	
Globigerinella aequilateris								R								R			
Orbulina universa	C		A	A			R	R	R			C	R			C	R	A	
Globorotalia menardii	A		A	A			C	C	R			A				A		A	C
G. truncatulinoides			C	A			C	R				C	R			C	R	C	R
G. tumida			R				R					C				A		R	
G. hirsuta				R			C	R				C						R	R
Pullenia quinqueloba			C				R					C	R			R	R		
Pulleniatina obliquiloculata			R	R				R				C				R		R	R
Sphaeroidina bulloides							C	R				R	R						
Cibicides pseudoungeriana	A		R				R	C				A				R		C	R
C. lobatulus		A																	

A=abundant; C=common; R=rare.

on of Foraminifera in northerly line of cores

6			7						8				11							13				14							
1	2	4	1	2	3	5	7	10	1	2	3	6	1	3	4	5	6	7	8	1	2	3	7	1	3	4	5	8	11	15	21
			R																	R											
																				R				C							
														R	R	R		R						R							
													R			R															
R				C	R				A	R			C	C			R							C							
																				A	A										
									C	C	R									R											
														C	R																
															R	C	R							R							
R										R															R						
R				C					R	R	R	C	R	R	R	C	R		A			C									
				A	R	R			R	R										R	R				R						
																R															
				R					R		R						R	R	R	R	R										R
		R	C			A	A			C	A			R		R	R	R		C	A	A	C						R		
										R				A																	
R		A	R		A	A	A	A		A	C	A		A		A	R	C				R	R						R		
C	A	A	C							A	A	A						C			R	C	A								
			R			C	C			R	C				A	A	R	A	C	C	C	A									
R	R	R	A	A		A	R		A	A	A		A	A	A	A	A	C	C	A	A	A	R			R					
			R			C				C				R	R	C	A	R	R												
A	R		A	C	C	A		R	C	R	C		A	A	A	A	A	A	A	C	C	R									
											C										R										
R	R	R	R	R		C	A	R			R	R		C	A	A		R		C	R	A	A			C					
												R									R	R				A		R		A	
															C																
											R										R		R								
	R	R							R		R									A	A	R									
	R	R	C	R	R				A	R	R		C			R								C					R		
A		C	A	R			A	A	A		R	A	A			A	C	A	A	A		A	A	A							
			R																			R									
C	A	A	C	C	A	A	A	A	R	A	A	C	R	A	A	A	A	A	A	A	C	A	C	R	A	A	A	A	C	A	C	A
A	A	A	R	A	A	A	A	R	R	A	A	A	C	A	A	A	A	A	C	R	A	A	A	A	A	C	A	R	C	A	R	A
R	A	A	R		A	A				C	A	A	R	A	A	A	A	A	A	R	C	A					A	R	R	R	R	A
A	C	C	A			R	A	C	A		A	A	A		C	C	R	R	C	C	C	R	A	A		C		A	A	C	A	A
	C	R		R	R	C	R			A	A	R		C	C	R		R				R			A		C	R				C
	A	C			A					A	C	A			C	R				C	C				A		C				
	C									C	R	R					R					R			C		A	R		C	C	
																R									R		A				
R	A				A	C	R	R		C	C	C		C	C	C	C	C	C	R	R	C	R		A		A					
	A	C		A	A	C				A	R	A		A	R		C	A	R		A	A			A		A					
R	C	R		R	A	R	C			A	R	A			R	R	A	R	A		C	R					C					
	R									C		C									C				C		R					
	R	R				R	R								R		C		R		R							R			
R										A	R				R				R		C						R					
	R	R			C	R				R		R		R			R					R					R					
												R										A	R									
	C	R								C		A									C	A	R									

According to Iselin (1936, p. 11), in the western North Atlantic there are three general areas of warm water: (1) The Gulf Stream is composed of very warm water originating in the tropics. (2) To the east and south of the Gulf Stream lies the large warm-water area of the mid-Atlantic known as the Sargasso Sea. (3) Overlying the continental slope, and west of the Gulf Stream, is the somewhat cooler slope water extending landward to the continental shelf. The abundant pelagic warm-water forms are quite characteristic of all these areas and are more abundant in the sediments underlying the Gulf Stream and the Sargasso Sea than on the continental slope. This is to some extent due to the warmer nature of these two water areas but it is probably also a result of the greater depth of water and a consequent smaller population of other than pelagic forms.

The Recent foraminiferal fauna of the continental slope is essentially homogeneous in the area sampled, although minor variations are noted which may be due to accidents of sampling and probably are of no great significance. In the Delaware Bay and Chesapeake Bay groups of cores, a greater population of *Uvigerina, Virgulina,* and *Angulogerina* in general was observed. Forms typically abundant in samples from the continental shelf are in general rare, and the shelf fauna can be distinguished from the slope fauna.

In studying this fauna particular attention has been paid to species which are especially characteristic of warm-water conditions. These are all pelagic forms living in warm water but not entirely restricted to such an environment. The following pelagic species are most useful, since they appear to be more or less indicative of relatively warm surface water areas (warm temperate to subtropical):

Globigerina dubia
Globigerinoides rubra
G. conglobata
G. sacculifera
Globigerinella aequilateris
Globorotalia menardii
G. truncatulinoides
G. hirsuta
Orbulina universa

At present these forms have a wide distribution in the North Atlantic. They are probably not all equal in value as indicators of warm surface-water temperature, but the abundance of one, or preferably more, species is apparently quite conclusive evidence. A small percentage of specimens of the above species occasionally occur in sediments underlying relatively colder water areas, but this is most often observed near the boundary of a warmer zone, and their presence in the sediments is probably due to being killed upon drifting into colder water. Also, the Gulf Stream has large eddies which invade relatively colder areas.

Invariably with this assemblage is found a great abundance of what is here tentatively called *Globigerina bulloides* and *G. inflata.* These

species cannot be used in distinguishing warm and cold water in the cores, however, since in many cases they occur in similar abundance in radically different faunal assemblages. Also their distribution in present waters is not so restricted as the species already listed. Other species also occur in abundance in some of the samples, but their presence is areally restricted, and most also occur in colder water assemblages.

Another characteristic feature of the Recent samples is the generally large number of species. It is not uncommon to have 60 species or more in one small sample. Particularly observable are the arenaceous forms. The warm-water specimens are occasionally large, especially in the Globorotaliidae, and also in *Nodosaria* and *Listerella*. These latter characteristics are in some cases quite useful supplementary criteria in the determination.

THE ARCTIC FORAMINIFERAL FAUNA

Beneath the top of most of the cores a fauna radically different from the Recent is present, at approximately 40 cms. beneath the top in some and not above 150 cms. in others; in a few cases it is not present although a 200 cm. section has been obtained. This fauna is composed of species living at the present time, but some are not present in the Recent fauna in the area covered by the cores. This lower fauna is at present essentially restricted to regions of cold water, mostly within the Arctic Circle or adjacent regions (Cushman, *et al.*, 1937). The most obvious general aspects of the fauna in comparison to the Recent are the relatively fewer Globigerinidae, the near or complete absence of the Globorotaliidae, and *Orbulina*, the smaller complete population, and the fewer species present. The following species, occurring commonly or in abundance, are characteristic:

Globigerina pachyderma
Elphidium advenum var. *margaritaceum*
E. sp.
Cassidulina laevigata
Cassidulina subglobosa
Nonion labradoricum
Virgulina squammosa
Bolivina sp. 1

The last three species are somewhat restricted in their usefulness and must be used with care. As this work has proceeded it has become increasingly apparent that it is difficult to apply any very strict rules in distinguishing these faunas. In every case the cold-water nature of the lower fauna, where present, has been determined relative to the Recent in the same core. In general the above criteria hold very well, but each core presents a more or less distinct problem in this connection.

DISCUSSION OF SPECIES

The more important species are illustrated in Plates 1, 2, and 3. Notes on some of these follow:

Pyrgo subsphaerica d'Orbigny

(Plate 3, figure 20)

Comparatively rare form, mostly present in cooler water samples.

Nonion cf. *grateloupi* (d'Orbigny)

(Plate 3, figures 7, 8)

Rather widely distributed in the Recent samples and also in the sections considered Arctic. Previous data show a more limited distribution.

Nonion labradoricum (Dawson)

(Plate 2, figures 13, 14)

Generally characteristic of the Arctic assemblages but also occurs in the Recent samples. Present data indicate that it is probably more common this far south than previously recorded.

Nonion pompiloides (Fichtel and Moll)

(Plate 3, figures 3, 4)

Relatively rare and in most cases does not occur in the fauna at the top of the cores.

Elphidium sp.

(Plate 2, figure 11)

Includes forms with a heavier and more opaque test than in *Elphidium advenum margaritaceum,* and probably more than one species. Wide areal and depth distribution in the present cores; particularly characteristic of the Arctic assemblages but also rare in a few Recent sections down to 2500 meters.

Elphidium advenum var. *margaritaceum* (Cushman)

(Plate 2, figure 12)

Forms included under this name are characterized by a more delicate, thin-shelled, and punctate test than the forms included under *Elphidium* sp. Possibly more than one species is here included, but further subdivision has not appeared necessary at present. Abundant in the Arctic fauna and also in transition phases between cold and warm-water assemblages. Very wide depth and areal distribution in the lower sections of the present cores. Common in the top of core 7, which was collected in water having a depth of 2579 meters, and recorded at the top of core 6-38, at 1710 meters.

Bulimina marginata (d'Orbigny)

(Plate 3, figure 23)

Common in some Recent samples, mostly in moderately shallow water, and occurring in a few Arctic samples.

Bulimina aculeata (d'Orbigny)

(Plate 3, figure 24)

Wide depth and areal distribution in Recent and older cold-water samples.

Bulimina affinis d'Orbigny

1922. *Bulimina affinis* CUSHMAN, U. S. Nat. Mus., Bull. 104, p. 103, pl. 20, fig. 6.

Very wide distribution in Recent and older core samples. More than one species probably here included.

Uvigerina peregrina Cushman

(Plate 3, figures 5, 6)

Abundant in more southerly cores, with greater abundance in Recent samples. Very variable in degree of ornamentation, from costate to almost entirely spinose.

Angulogerina angulosa (Williamson)

(Plate 3, figures 10, 11)

Particularly common in Recent samples of cores from comparatively shallow water but also observed in a few cases in Arctic assemblages from deeper water.

Angulogerina sp. 1

(Plate 3, figures 12, 13, 14)

A smaller, more slender, and more costate species than *Angulogerina angulosa;* recorded abundantly in the Recent samples down to 1450 meters.

Cassidulina laevigata d'Orbigny

(Plate 2, figures 6, 7, 8)

Rare to common in Recent samples but constituting a large percentage of the cold-water samples in the cores. Wide distribution at present, but from published records appears to be most prevalent in cooler waters (Cushman, 1922, p. 122) and is common in the Arctic. Has a greater depth range in the present Arctic assemblages than *Cassidulina subglobosa.*

Cassidulina subglobosa H. B. Brady

(Plate 2, figures 3, 4)

Common or abundant in many of the Recent shallower water core samples and more abundant in the Arctic assemblages, particularly in cores taken from moderate depths. Apparently more or less characteristic of the upper part of the continental slope.

Globigerina bulloides d'Orbigny

(Plate 3, figures 15, 16)

Most consistently abundant single species, occurring in all the samples and therefore of no significance in temperature determinations.

There has been considerable confusion as to what should be referred to this name; the present species is not true *Globigerina bulloides* but is the form which goes under that name in this part of the Atlantic. The writer's identification is based largely upon Cushman (1924, Pl. 2, fig. 1-4). If several species are represented in the present samples they are so nearly alike that they would be of doubtful use in the present study.

Globigerina inflata d'Orbigny

(Plate 3, figures 18, 19)

Also very abundant in most of the samples. Cushman (1924, p. 13) assumes it to be a benthonic form since it does not live in the tropics and therefore does not have the same distribution as species of *Globigerinoides.* Common in the present cold-water assemblages but a little less so in the Recent samples in most cases.

Globigerina dubia Egger

(Plate 1, figures 14, 15)

Abundant in samples which contain a warm-water assemblage but also occurs in other samples. Most common along the path of the Gulf Stream and less so on the continental slope.

Globigerina pachyderma Ehrenberg

(Plate 2, figures 1, 2)

Recorded from the Arctic by Brady and from the Antarctic by Pearcey, its distribution is thought to be entirely confined to cold waters. Brady did not find it in the pelagic tows in the Arctic but only in the bottom samples and on that basis it is considered to be of benthonic habitat (Cushman, 1924, p. 15).

Characterized by the four outside chambers with slightly depressed sutures, with the aperture slit-like along the last formed chamber; the surface of the test has a granular appearance, and the wall is quite thick. Considered one of the most useful forms in identifying cold-water assemblages in the cores.

Globigerinoides rubra d'Orbigny

(Plate 1, figure 12)

A common tropical water and Gulf Stream form found in some abundance on the continental slope. The test in many cases is not so pink as in warmer waters and it is likely to be confused with *Globigerinoides sacculifera*. May be distinguished from the latter species, however, by the difference in surface ornamentation of the test. A good indicator of warm surface water and does not occur in typically cold-water samples from the present cores.

Globigerinoides sacculifera H. B. Brady

(Plate 1, figures 16, 17)

Common in the Recent core samples, particularly near the Gulf Stream region. Not present in the Arctic assemblages and therefore a good indicator of warm surface water. Distinguished by the projected last chamber, and in specimens lacking this by the reticulate character of the surface of the test. Typical of very warm-water areas at the present time.

Globorotalia

Globorotalia is quite abundant in the Recent samples underlying surface areas of warm-water, and the species are among the most useful indicators of such in the present cores. The species are sufficiently distinctive to separate easily (Pl. 1, figs. 3-7, 10, 11). In general, the specimens are large.

Buliminella elegans var. *exilis* (H. B. Brady)

(Plate 3, figure 17)

Abundant to rare in most samples, except in the deepest cores studied.

Virgulina squammosa d'Orbigny

(Plate 2, figure 10)

Most common in more southerly core groups. Greatest abundance characteristic of cold-water fauna in many cases.

Cibicides pseudoungeriana (Cushman)

(Plate 3, figures 1, 2)

Typical in warm-water assemblages. Very abundant in many Recent samples.

Globigerinella aequilateris (H. B. Brady)

(Plate 1, figures 11, 13)

Rare in the present cores, but where present probably quite indicative of warm surface water conditions, judging from the known distribution of the species.

Pullenia quinqueloba (Reuss)

1924. *Pullenia quinqueloba* CUSHMAN, U. S. Nat. Mus., Bull. 104, pt. 5, p. 42-43, pl. 8, figs. 5-9, 11.

The distribution given by Cushman (1924, p. 43) "seems to be in cold deep waters as a rule." Occurs in the Recent fauna over most of the depth range covered by the cores and is in most cases absent from the Arctic assemblages.

A variety of arenaceous forms occur mainly in the warm-water samples, only a small number of which are listed in Tables 2 and 3. These constitute a very minor percentage of the census and have not been used to any extent in the present study.

FAUNAL DATA

GENERAL STATEMENT

This part of the work on the present cores is concerned entirely with the foraminiferal microfaunas and their direct implications. The detailed sedimentary data enter into the general conclusions and are to be presented elsewhere. The following deals with a discussion of the faunas by cores. The data are presented graphically in Tables 1 and 2 and in Figures 2, 3, and 4.

LINE SOUTH OF CAPE COD

Core 1. The top sample has a warm-water fauna somewhat different from that farther down on the slope. Few Globorotaliidae are present, and there is an abundance of *Bulimina*, together with *Angulogerina* and *Bolivina* sp. 1. The sample at the bottom, 80-85 cms., carries a fauna considered of probable Arctic type, although the typical *Globigerina pachyderma* was not observed; *Elphidium advenum margaritaceum* and *Cassidulina* are abundant, and warm-water species are rare. It probably represents a transition fauna.

Core 2. The top sample has a moderately warm assemblage, but at 30-40 cms. is a fauna which appears to be of warmer type, since *Elphidium* and *Cassidulina* are present in the top and absent in this lower section. At 63-70 cms. is a definitely Arctic assemblage continuous in all sections to 289 cms.

Core 3. The trend toward cold-water types is evident at 30-34 cms. (sample 2) in the introduction of *Globigerina pachyderma* and the abundance of *Elphidium* and *Cassidulina*. At 63-70 cms. the fauna is definitely Arctic, but *Globigerinoides rubra, G. sacculifera,* and *Orbulina universa* are present. This sample is considered a true transition between the two types, above and below. From here the Arctic assemblage is present to 289 cms. Core 13 shows about the same vertical distribution, but an unusual abundance of *Globigerina pachyderma* at the bottom (180-190 cms.) may suggest very cold water. In core 4 the Arctic fauna is met at 35-42 cms., and cold-water species increase in abundance toward the bottom of the core (244 cms.).

TABLE 3.—*Distribution of Foram*

Core	1–38		2–38		3–38		4–38		5–38					6–38				7–38		12–38		
Sample	1	3	1	3	1	3	1	3	1	3	4	6	7	1	2	4	5	1	3	1	2	
Saccamina sphaerica	C				C									R	R						R	
Proteonina difflugiformis	R																	R				
Eggerella																						
Textularia					R		R															
Karreriella bradyi							R	C					R									
Quinqueloculina seminulum											R			R		R	R					
Q. sp.				R							R						R					
Triloculina tricarinata				R							R				R				R			
Pyrgo subsphaerica											R											
Other pyrgos												R						R			R	
Robulus							C								R							
Marginulina bachei																						
Lagena							R	R	C		R		R									
Polymorphinidae					R		R	R	R				R							R	R	
Nonion cf. *grateloupi*	R						C			R	R	R		R	R			C		R		
N. labradoricum		C	R			A	R	R	C		A		R									R
N. pompiloides								R	R		R	C	R									
Elphidium sp.		A	R	R		C					R	R		R			R	R	R			
E. advenum var. *margaritaceum*				C		C				C	A	C		R			A		C			A
Bulimina marginata		R								R							R					R
B. aculeata	A		R		C		A	C	C	C	R		A	R	R					R	C	
B. cf. *affinis*	R	R	R	R		C	R	R			R	R	R	C				C		R		R
Uvigerina peregrina	C		C		A		A	R	A		R	A		A				A		A	A	
Other uvigerinas																						
Angulogerina angulosa																						R
A. sp. 1	A				A		R	A	A	C	R				C						A	
Buliminella elegans var. *exilis*	A	R	C	R			C	R	C		R		R	C	C	R		A	R	C	A	R
Virgulina schreibersiana			R		R					R												
V. squammosa	A	A			C	A		C	R	C	C	R		R	C				R	C	A	C
Bolivina subaenariensis										R								R		R	R	
B. subspiniscens	A				C		C	C	R			R		R	C			R			A	
B. sp. 1	R						C	R	R		R		R				R	R		C		
Gyroidina soldanii							R				R		R									
Cassidulina laevigata	R	C	C	A	R	A	R	C	C	A	A	A	A	R		R	R		R			A
C. subglobosa			A	C	R			A				A					C		C			A
Cassidulinoides bradyi																						
Globigerina bulloides	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		R	A	R	A	A	A
G. inflata	A	R	A	R	A	A	A	A	A	A	R	A	A	A	A			A		A	A	R
G. dubia	C	R			C		A	C	A	R	R	C	A	C	A					R		
G. pachyderma		A	C	R		A	R	A	R	C	A	C	C		R	C						A
Globigerinoides rubra	C			R	R		R	C	R	R		R	R	C	A			R		R	R	
G. conglobata	C		R		R		C	R	R	R			C	R	R			C		R		
G. sacculifera								R					R					R				
Orbulina universa	C				C		C			R		R	R	C	A			R		R	C	
Globorotalia menardii	A				C		C	C	R	R			R	C	A			C		R	A	
G. truncatulinoides	R			R	R		C	R					A		R			C			R	
G. tumida			R		R																	
G. hirsuta	R						R			R			R					C				
Pulleniа quinqueloba	R		R		R		R		R	R		R	R	R	R							
Pulleniatina obliquiloculata					R										R					R	R	
Sphaeroidina bulloides	R				R			R	R	R			A	R	R			R				
Cibicides pseudoungeriana	A		R		C		A	C	R				A	A	A			C		R	C	
C. lobatulus							R															
Globigerinella aequilateris		R																C				

A = abundant; C = common; R = rare.

of Foraminifera in two southerly groups of cores

12–38			20–38				23–38			8–38	9–38		10–38	11–38	13–38			14–38			15–38			19–38				22–38			
1	2	3	1	2	3	6	1	4	7	1	1	3	1	1	1	2	4	1	2	3	1	3	4	1	2	3	4	1	3	4	7
	R		R				R								R													R	R		
				R			R	R					R	C																	
				R														R												C	
										R												R									
				R												R															
		R			R					C				R			R		R		R	A	A	R						R	
					R																		A								R
						R													R												
										R							R						A				R		R		
	R																		R								R		R	R	
			R							A	R										R	R	R			R					
										C		R										R	R								
			C	R	R					C	A	A	A	A		R	R		R			R	R		C	C	C				
R	R							C		A	C		R	C	R						C	R	A		R				R		
R			R			R	C	R		C	C	A	A	R	C		R	R	R			R		R	R	C		R	R		R
		R			R	R			R	R				R	R		R						C			R	R	R			
					R	R			R	R		C	R		R		R		R		R	R	R		R						
					A				R	R				R			R						R		R		R	R			
		A			C	A			C		R	R	A				A					R	A			R					
		R							R	A	A	A	A	A	R				C	R	C	C	C	R		R	R		R		
R	C			C		R	C	A			R	R		C	A	C	C	C	R					C	R	C	R		R	C	C
R		R	R			R				A	A	A	C	A		R	C	R			A	R	C	R	R	C	R	R			
A	A		A	R											A	A		A						R		A		A		R	
										R		A														R	R				
		R								A	R	A	C	C					R			A	C		R	R	R			R	
	A		A	C												A		C										C		R	
C	A	R	A	C		C	A	C	R	C	C	C	R	A	C	C		A	A	R	R	R	C	A	A	A	A	C	A	A	A
						R			R	C	R	C	R	R				R			C	R	R								
C	A	C	R	C	R	C	R	R	R	C	A	A	A	A		A	A	C	A		R			A	A	A	A	R	C	R	A
R	R									C	A	A	R	A	R	R	R	C	C	R	A	A	A	R	R	R	C		R	R	R
	A		C	C	R		C	R							A				R		C			R					A	R	R
C			C					R			A	A	A	A	R		R		C					R		C	R	R	A	C	C
															A				R			C					A				
		A	R	R	A	A		R	A		C	A	A	A	R	R	A	R	R		A	A	C	R	R	R	C		R	R	
		A			A	A		A	C	A	R	R	A	A		A			R		A	A	A		R	R	A	R	R		
										R	C	A		R							R			R							
A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		A	A	A	A	A	A	A	A	A	A	A
A	A	R	A	A		A	A	A	A	A	A	A	A	A	A	A	A	A	A		A	A	C	A	C	A	C	A	A	A	A
R			C	C			C	C		A	A		C		R			R	C	A	R	C		C			R	C	C	R	
		A			C	A			A								A		C						R		R			C	C
R	R		R	C			R	C		C	R	R	R	R	R	C	R	R	R	A	C	R	A	R		R	R		R	C	
R			R	C				R		C	R	C			R	C		R	C	A	R		R					R	R	R	
										R		R								R			R								
R	C		C	C		R		R		A	R	R		R	C	C			C	A	R		A	R	R	R	R	R		R	
R	A		C	A			A	C		A	R	C	R	R	C	A		C	A		R	R			R	R		C	R	R	R
	R		C	R		R	R	C		R	R		R	R	R			R				R	R	R	R			R			
			C																		C								R		
			R				R	R							C			R								R					
			R	R				R						R	R																
R	R			R				R		R		R	R	R				R	R		R										
				R																									R		
R	C		C	A						A	C	A	R	R	R	A		R	R		R	A	A	R		A	C	R	R	R	R
																							A								

Cores 5 and 6. Although rather short, they reached an Arctic fauna at 56 and 72 cms., respectively. A somewhat transitional assemblage is shown in core 5 at 48-56 cms., but the generally cold-water nature is evident.

Core 7. At 33-43 cms. was found a fauna decidedly warmer in type than that at the top. The typically warm-water species are here abundant and are only rare or absent at the top. From 77-128 cms. the assemblage is transitional, and at 118-128 cms. the fauna is slightly more Arctic. From 150-225 cms. the fauna is strictly cold-water. In core 11 this mixture of Arctic and warm-water types appears at 68 cms. and continues to 194 cms., the bottom of the core. It is somewhat difficult to interpret the associations observed in these samples (3-7), but they are tentatively considered to be near the line between cold and warm-water conditions.

Core 8. This shows a very abrupt swing to an Arctic fauna at 53-58 cms. and continues to 109 cms.

Cores 14, 15, and 16. These cores of Stetson's collection have come from beyond the bottom of the continental slope at the western edge of the ocean basin. Core 14 shows an Arctic fauna at 61-65 cms. with a possible transition assemblage at 58 cms. Sample 4 of this core (67-68 cms.) shows a decidedly warm-water fauna, and at 72-73 cms. there is another transitional one, while at 77-78 cms. a typically Arctic assemblage is shown. From 106-160 cms. *Globigerinoides sacculifera* is common, and *G. rubra* is rarely present from 106-126 cms. These are in an otherwise typically cold-water fauna, and the present interpretation is that those more or less isolated occurrences of warm-water species might be disregarded. At 296-299 cms. the fauna contains such a variety of warm-water types that it certainly represents a swing toward warm surface water conditions. It is interesting to note that *Elphidium* and *Cassidulina laevigata* are almost entirely absent in this core. *Cassidulina subglobosa*, however, is abundant in many of the samples; *Virgulina squammosa* is abundant in a few. The remainder of the census is made up almost entirely of Globigerinidae together with the Globorotaliidae in the warm samples.

At present it is difficult to interpret the lower assemblages in cores 15 and 16. At least one Arctic microfauna is present in both cores. It seems advisable to postpone discussion of these cores until further collecting is done from the deep-water area of the Atlantic basin and until faunal criteria from these areas can be better compared.

DELAWARE BAY GROUP

Core 1-38. An Arctic fauna appears at 132-141 cms. beneath the top and continues to 244 cms. The top sample contains a moderately warm-

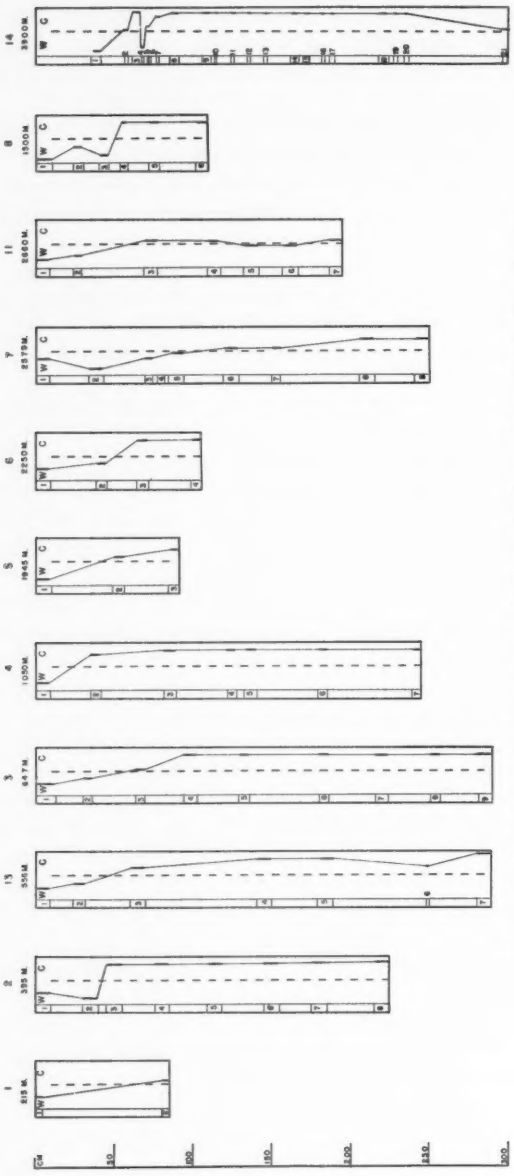

FIGURE 2.—*Relative water temperature indicated by faunas in northerly line of cores*
W = warm water; C = cold water.

water fauna. Core 3-38 has a slightly warmer water fauna at the top, and an Arctic fauna appears at 111-119 cms., continuing to 264 cms. At the bottom the fauna is interpreted as indicative of colder-water conditions than that shown in core 1-38 or in the upper part of the same core. This latter conclusion is based upon the concentration of typically cold-water types to the exclusion of any other species.

Core 2-38. The faunal evidence is confusing, but the writer's tentative interpretation is that the fauna of the entire core borders on an Arctic type. If this is true, the Recent fauna is not represented at all. Core 4-38 shows much the same condition, but in the top section Arctic and warm-water types are definitely mixed. This condition also holds for the bottom section at 107-115 cms. but is not true for the middle section at 55-63 cms.

Core 5-38. This has a greater variety of warm-water forms at 61-70 cms. than at the top and is interpreted as indicative of warmer-water conditions than the Recent assemblage. A typically Arctic fauna occurs from 98-117 cms. and 119-126 cms. A trend toward a warmer fauna is seen in the introduction of *Globigerinoides rubra* and *Orbulina universa*, while at the bottom (144-149 cms.) a definite warm-water fauna is present.

Cores 6-38 and 7-38. They likewise have a greater number of warm-water species below the top than in the top sections, at 111-118 cms. and 81-88 cms. respectively. In the former core, which is also the longer one, there is a rather abrupt transition to an Arctic assemblage at 122-130 cms., and this continues to the bottom, at 175 cms. The lower sections of this core are notable for the few species and the relatively few individuals. Core 7-38 shows a trend toward an Arctic fauna at the bottom (146-156 cms.) but this is concluded mainly on the basis of the paucity of species and individuals.

Core 20-38. The cold-water types appear at 92-100 cms. and continue to the bottom (208 cms.), with a colder assemblage in the two lower sections than in the two directly above.

Core 22-38. The section at 68-76 cms. is suggestive of warmer conditions than that at the top. At 105-112 cms. a transitional fauna is present, and an Arctic fauna occurs from 127-171 cms. In core 23-38 the Recent fauna is uniform in the upper 131 cms., and a uniformly Arctic fauna is present in the bottom part (148-235 cms.).

Core 21-38. This contains a Recent fauna in the upper 114 cms. The lower part (123-157 cms.), however, contains a fauna which has *Hantkenina* and is distinctly Tertiary in aspect, probably Eocene. A few species were observed by the writer which appear close to Cretaceous forms. The fauna is somewhat unique and is being described by Cushman. The Eocene fauna occurs in a white rather hard matrix. At 120-

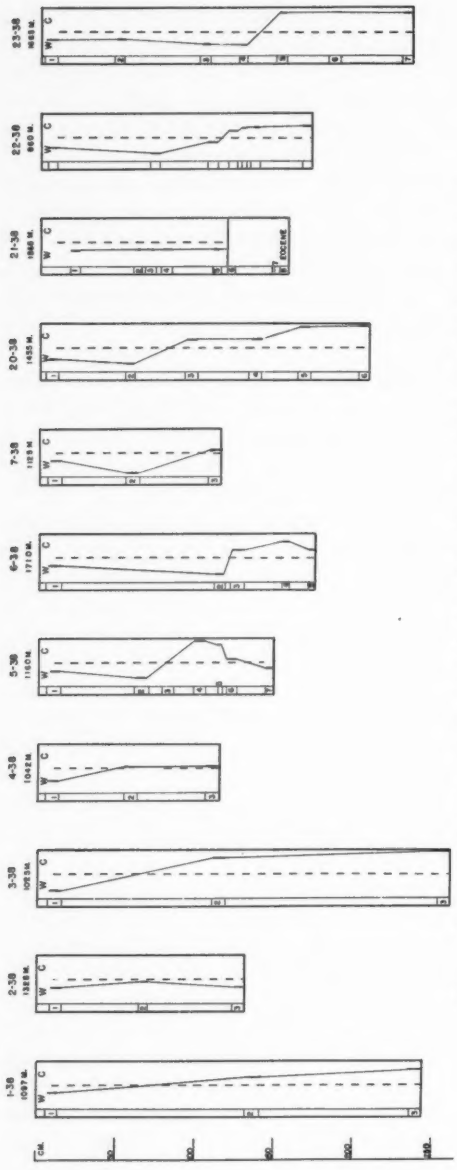

FIGURE 3.—*Relative water temperature indicated by faunas in Delaware Bay group of cores*
W = warm water; C = cold water.

121 cms. a band of this white material is separated from the bottom section by 2 cms. of the dark fine-grained sediment containing the Recent sediment in the upper part of the core. In this white band occurs a mixture of the Eocene and Recent species.

CHESAPEAKE BAY GROUP

Cores 8-38, 9-38, 10-38, and 11-38. They have lengths of 110 cms., 143 cms., 187 cms., and 138 cms. respectively and did not penetrate the Recent fauna. The warm-water assemblage throughout is typical of the continental slope. In core 11-38 the fauna in the lower section, from 66-134 cms., is thought to represent a slightly warmer assemblage since *Globigerina dubia* is abundant in this range and was not observed in the top section.

Core 12-38. This has a distinctly warmer assemblage at 100-108 cms. than at the top and contains a cold-water fauna at 139-147 cms. In core 13-38 the Arctic assemblage appears at 66-74 cms. and continues to the bottom of the core at 124 cms. Above this the fauna appears to be uniform and of a moderately warm-water nature.

Core 14-38. *Globigerina pachyderma* is common at 73-80 cms. in association with an abundance of warm-water types and does not occur either above or below. This discordance is difficult to interpret with any assurance.

Core 15-38. This shows no suggestion of a cold-water assemblage. The bottom section (176-183 cms.) has a fauna of warmer type than that at the top. Core 19-38 has a consistent fauna which shows some colder aspects at the bottom of the core (165-175 cms.) and probably represents a transition into a colder fauna not reached by this core.

INTERPRETATION OF FAUNAL DATA

GENERAL STATEMENT

The submarine coring done to date by Stetson and whose faunas are here described is largely in the nature of a reconnaissance. This is also true, to a certain extent, of the faunal studies themselves. For these reasons the faunal interpretations are tentative and subject to revision as further study of additional material is made.

The questions raised by Cushman, Henbest, and Lohman (1937, p. 1304) in regard to the efficiency of the coring tube are still pertinent to the interpretations of these faunas and have been discussed in part. Experience with a large number of cores and their microfaunas has led the writer to agree that a comparatively undisturbed section of the bottom is obtained. Some faunal mixing may occur in the upper part of a core taken in extremely soft material, but this need not affect accuracy of

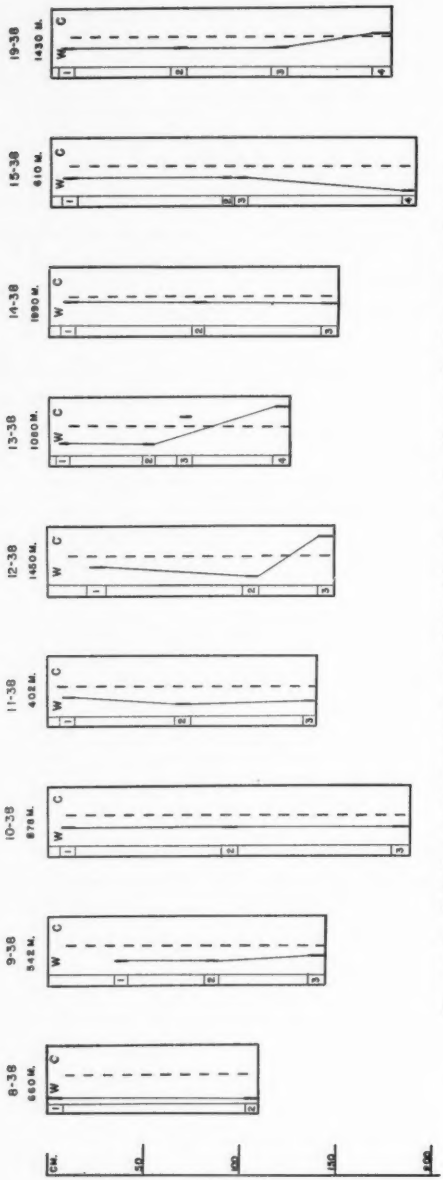

FIGURE 4.—*Relative water temperature indicated by faunas in Chesapeake Bay group of cores*
W = warm water; C = cold water.

sampling because a sample can be taken below this mixed zone. "Whether the fauna in the lower part of the core may have been swept from near shore by currents not now active" (Cushman, *et al.*, 1937) is an important problem which cannot be answered satisfactorily until more evidence is obtained. Such a circumstance would seriously affect the interpretations here offered.

The most important factual contributions of these data are the recognition of one or more Arctic or sub-Arctic faunas beneath the sediments being deposited at the present time and their occurrence over a large area of the continental slope, extending to the western edge of the Atlantic basin.

THE ARCTIC FAUNA

The Arctic type assemblage was without a doubt deposited when the water temperature was much lower than it is at present. At present an assemblage of species is being incorporated into the sediments which is quite characteristic of warm water and in general is similar in type, but not degree, to faunas of tropical waters. The general uniformity of the major aspects of this present-day fauna over all the continental slope samples precludes its accidental introduction by a warm-water current such as the Gulf Stream; it occurs at a considerable distance from the Gulf Stream in many places. It must therefore be considered as typical of these areas of the warm slope water.

The Arctic foraminiferal assemblage, then, is quite foreign to the continental slope at the present time and is characteristic of cooler waters such as in the Arctic and sub-Arctic regions. According to Cushman (1937),

> "the conclusion seems warranted that the material . . . represents a fauna of cold environment, such as that now present within the Arctic Circle."

This statement does not precisely apply to all the assemblages which are here designated as of cold water aspect but it is true of one or more samples beneath the surface in cores 2, 3, 4, 6, 7, 8, 13, 14, 1-38, 3-38, 5-38, 6-38, 12-38, 20-38, 23-38, 13-38, and 22-38. In other cores of the present series and in some samples of the cores listed above the cold-water assemblages do not seem typically Arctic.

The Arctic microfauna is similar to that identified by Cushman from Georges Bank (1936). Several short cores were collected by Stetson (1936) from the bottoms of the three Georges Bank canyons investigated by him. Four of them penetrated the coarse silt on the surface, which contains Recent warm-water Foraminifera, to a fine-grained silt, at a depth of a few centimeters, containing an Arctic assemblage. The locations of the four Georges Bank cores containing the Arctic Foramini-

fera are as follows: Core 1, N. Lat. 40°23′03″, W. Long. 68°08′, depth 943 meters; core 2, N. Lat. 40° 20′, W. Long. 68°09′, depth 633 meters; core 5, N. Lat. 40°20′40″, W. Long. 67°51′30″, depth 864 meters; core 6, N. Lat. 40°20′40″, W. Long. 67°50′40″, depth 530 meters. Cores 1 and 2 are from the middle of Stetson's canyon I, and cores 5 and 6 are from the middle of his canyon II.

A similar cold-water fauna has been obtained from the basal part of a core (148-164 cms.) taken "about 150 land miles South of New London, Connecticut, and 130 miles East of Atlantic City, New Jersey" at a depth "calculated to be about 2200 meters." (Cushman, *et al.*, 1937). The geographic location is 72° W. Long. 39°13′ N. Lat. In commenting on this lower fauna Cushman (1937, p. 1303) states:

> "The globigerinids belong to species, particularly *Globigerina pachyderma* Ehrenberg, which are known as bottom living forms mostly confined to the Arctic and within the Arctic Circle. With them are species of *Cassidulina, Bulimina, Virgulina, Eponides,* and *Elphidium,* which are characteristic of the Arctic region . . ."

Judging from its vertical position and geographic location, this fauna is undoubtedly to be correlated with the similar one in the present cores.

Several submarine cores were collected by Piggot across the North Atlantic which have been studied by Bradley, Cushman, and others (1937). The complete report of this study is not yet published, but the present writer has been privileged to examine some of the foraminiferal material and data at the Cushman Laboratory, through the generosity of Dr. Cushman. One or more Arctic faunas has been identified from these cores, and the character of this assemblage is similar to that in the present cores. The upper Arctic fauna in the former cores is, in the writer's opinion, to be correlated in time with the upper one in the continental slope cores.

The fact that all the species of the Arctic microfauna are still living indicates that it was deposited at a fairly recent time. It is to be correlated with one or more phases of the Pleistocene ice advance, during which time the oceanic waters must have been considerably cooled, especially near the southern limit of the ice sheet. The Arctic microfauna which occurs directly beneath the Recent, and which is the only one recognized in most of the cores here discussed, probably represents some phase of the Wisconsin stage. In most cases, only the latter part of this stage is certainly shown, since the majority of the cores do not penetrate to the bottom of the upper Arctic fauna.

In Core 14, taken in the Atlantic basin at a depth of 3900 meters, there are two Arctic microfaunas separated by a warm-water fauna. The interpretation of this occurrence presents difficulties because of the vertical distribution of the different types. The upper Arctic material has a

thickness of only 7 cms., and the lower material ranges through at least 164 cms.; the warm-water fauna separating these occurrences came from a band only 1 cm. in thickness, and immediately adjoining samples above and below contain a radically different and distinctly cold-water assemblage. It is possible that the two cold-water faunas represent two separate glacial maxima of Wisconsin time, but more faunal data are needed from this area.

According to recent temperature data from the western North Atlantic (Iselin, 1936), the water below a depth of about 800 meters above the continental slope is uniformly cold (about 5° C. or less) and does not have a seasonal variation. The lowered temperature during a time of ice advance would have had most effect upon the surface layers of water, above about 800 meters. The effect upon the deeper water must have been relatively slight since these waters are uniformly cold at the present time, being composed of Arctic water. The ecological significance of the lowered bottom temperature insofar as the Foraminifera are concerned may have been slight since the change probably was relatively small. It would be expected that the near-surface temperature would have been lowest near the ice sheet, with true Arctic surface conditions prevailing much farther south than at present. Under such conditions there would be a zonation similar to that at present, with progressively warmer water away from the ice border. A possible suggestion of such zonation is observed in comparing the Arctic fauna of the more southerly cores with that of the more northerly cores.

In the southerly cores the cold-water fauna differs from the northern fauna, in many cases, in having rare occurrences of typically warm-water pelagic species.

The oceanic circulation also must have been affected by the presence and position of the ice sheet. This would further alter the positions of cold- and warm-water areas other than by a simple zonation away from the ice. The path of the Gulf Stream, for example, must have been somewhat different from its present path. It is possible that study of sufficient additional core material may give some data on this point.

POSTGLACIAL WARM-WATER FAUNA

In six of the present cores an assemblage of Foraminifera occurs beneath the present-day assemblage and above the Arctic fauna which contains a greater abundance of typically warm-water species than in the top sample of the same core. This may be explained as due to accidents of sampling, but since it is rather widespread it appears that such is not the case. Its nonrecognition in other cores may be due to insufficient sampling. This observation has been made in cores 2, 7, 5-38, 7-38, 22-38,

and 12-38, and it may be present but not recognized in other cases. The geographic position of these cores ranges from 39°57′ N. Lat. to 37°21′ N. Lat., and from 70°41′ W. Long. to 74°21′ W. Long. Assuming that this observation is not due to unavoidable errors of sampling, it suggests that there existed during some part of postglacial time warmer surface waters than at present overlie these positions on the continental slope. This may represent a local postglacial shift of the Gulf Stream nearer the shore or some other, smaller area of water. Another possibility is that it represents generally warmer surface-water conditions. The Foraminifera concerned in this observation are pelagic types, and therefore the possible interpretations can apply only to the surface-water layers.

In recent peat bog studies in eastern Canada Auer (1930) has collected evidence which points to one warmer postglacial climatic period than at present obtains in that region. This conclusion is based upon pollen analysis and shows that the present spruce forest is a recent development for the area. Sears, in his survey on the use of pollen analysis in dating cultural deposits, states (1937, p. 66) that

> . . . "while the events of early post-glacial climate are still obscure and no doubt confused by irregular edaphic conditions along the retreating ice front, there is fairly clear evidence of the post-glacial warm dry maximum. . . . This hypothesis is not without support from floristic and ecological sources."

The evidence of postglacial warmer faunas in the cores is of sufficient possible significance to merit further investigation. The recognition of warmer postglacial climates on the land is very suggestive in this connection.

PELAGIC AND BENTHONIC TYPES

The species which are characteristic of the Arctic fauna in the cores are usually considered bottom-living types in shallow water, such as *Globigerina pachyderma, Cassidulina, Elphidium, Virgulina,* and *Bulimina* (Cushman, 1937). The occurrence of this assemblage under such circumstances has been used to "indicate considerable changes in sea level" (Cushman, *et al.,* 1937) during the Pleistocene. In view of the far-reaching implications of such a suggestion, particularly as it applies to the hypotheses for origin of submarine canyons, the ecologic information upon which it is based deserves to be examined.

The benthonic nature of *Globigerina pachyderma,* reported by Cushman (1924, p. 15) apparently is based upon Brady's record of it; he found that it occurs "only in bottom dredgings, not in the pelagic gatherings." Murray (1897, p. 20) recorded *G. pachyderma* in the pelagic samples.

> "In the Arctic and Antarctic regions *Globigerina dutertei* and *pachyderma,* together with very minute specimens of *G. bulloides,* appear to be the only forms present in the surface water."

The reliability of *Elphidium* as an indicator of shallow water has recently been questioned by Cushman (1937) since it occurs at several stations in the Pacific at considerable depth (Cushman, 1914, p. 30-34). The genus occurs in the Recent assemblage in nine of the present cores which have a depth range from 402 to 2579 meters. In all but one or two of these occurrences *Elphidium* is rare. The genus is most commonly seen in shallow water, such as on the continental shelf, and some species have been observed living commensally with algae.

Species of *Cassidulina* are rare to common in about half of the Recent samples of the present cores, and the same observation has been made on the species of *Virgulina* most commonly associated in the Arctic assemblages from the cores.

Considering the above facts, it does not seem valid to conclude that the Arctic fauna necessarily indicates any shallower conditions than does the Recent fauna. Relatively little is known about the habits of living Foraminifera, and until a great number of pertinent observations are made it will be difficult to prove details of interpretation based upon depth distribution. The writer is inclined to suspect that more species live in the upper zone of sunlight penetration than have been observed. They may live in association with algae or other things in this zone of maximum life development. The failure to find pelagic types in certain tows whose skeletons are present in bottom gatherings in any region is negative evidence and not necessarily conclusive. In the experience of the men working at the Woods Hole Oceanographic Institution, Foraminifera are only rarely observed in the average plankton tows. This is true even in areas where pelagic forms are known to live in some abundance.

If extensive reworking of deposits has occurred on the continental slope, or if currents not now active carried the shallow-water types out from shallow water and deposited them in deeper water, their occurrence can be easily explained. This is a definite possibility, since the generally lowered sea level obtaining during an ice advance must have redistributed some of the sediments of the upper part of the continental shelf. There is no evidence of wear due to transportation on many of the Foraminifera examined by the author. This is not necessarily a criterion, however, because of the small size of the tests and the lubrication afforded them by being constantly in the water, as commonly observed in washing foraminiferal material. The author is aware of no evidence that reworking of deposits is occurring on a large scale on the deeper parts of the slope at the present time. The distribution of species in the Recent fauna appear to suggest that such is not the case. It must be admitted, however, that

some associations in the samples from the cores suggest a possibility of reworking in isolated locations, but this is not a general observation.

CONCLUSIONS

(1) The foraminiferal microfaunas from several submarine cores from the continental slope of the western North Atlantic have been examined and described.

(2) Beneath the Recent fauna there is a widespread Arctic to sub-Arctic assemblage not now living in this region of the continental slope. This is considered Pleistocene, and probably Wisconsin in age, and is to be correlated with Arctic faunas reported from other cores in the western North Atlantic.

(3) Near the edge of the ocean basin two Arctic faunas have been observed, separated by a warm-water fauna. This may represent two ice advances, but the evidence is not conclusive.

(4) In a few cores a fauna of warmer-water aspect than the present one occurs at a short distance beneath the top of the cores. This suggests a possible postglacial shift in warm-water areas.

(5) Indirect evidence suggests that water temperature may be a prime factor in the distribution of Foraminifera. Evidence for considerable change in sea level is considered inadequate.

(6) The conclusions are tentative and will be conditioned by further study of additional core material.

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Amherst College, Amherst, Mass.

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Contribution No. 204, Woods Hole Oceanographic Institution.
Project grant 238-38.

EXPLANATION OF PLATES

PLATE 1

Figure — SPECIES TYPICAL OF WARM-WATER SAMPLES

(1, 2) *Globorotalia menardii* (d'Orbigny). (×54.) (1) ventral view; (2) dorsal view. Core 11, sample 1.

(3, 4) *Globorotalia hirsuta* (d'Orbigny). (×54.) (3) ventral view; (4) dorsal view. Core 11, sample 5.

(5, 6, 7) *Globorotalia tumida* (H. B. Brady). (×54.) (5) ventral view; (6) side view; (7) dorsal view. Core 8, sample 1.

(8) *Globigerinoides conglobata* (H. B. Brady). (×60.) Core 11, sample 5.

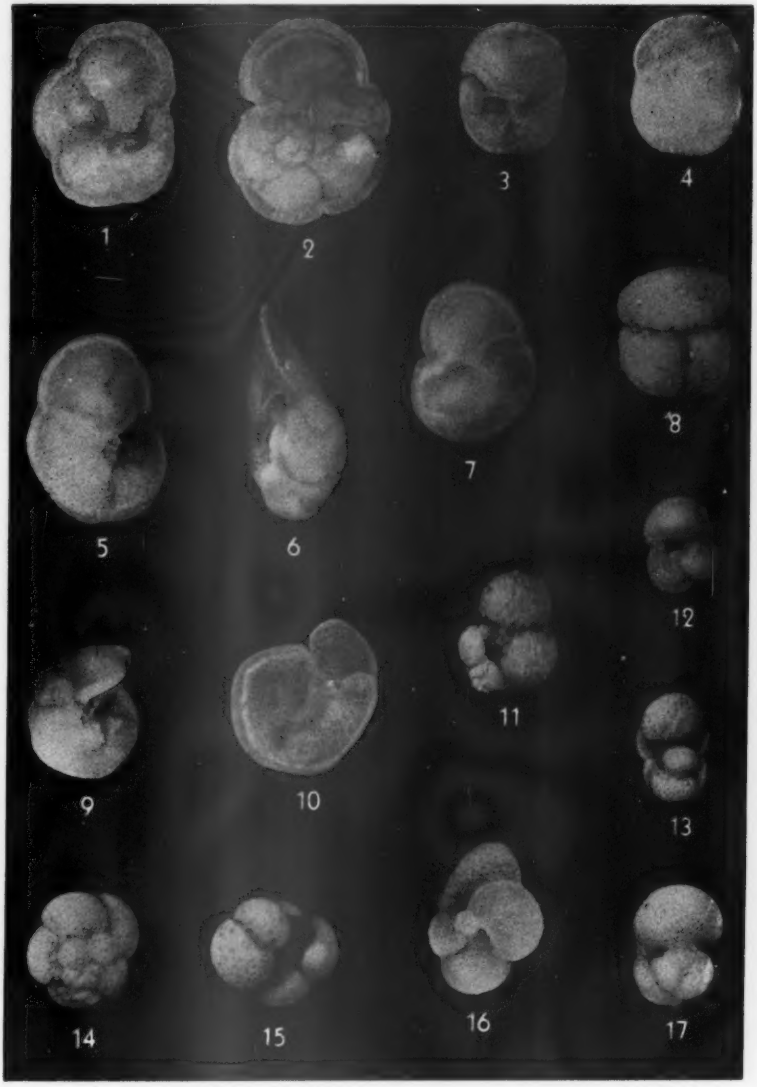
(9, 10) *Globorotalia truncatulinoides* (d'Orbigny). (×58.) (9) dorsal view; (10) ventral view. Core 11, sample 5.

(11, 13) *Globigerinella aequilateris* (H. B. Brady). (×60.) (11) side view; (13) apertural view. Core 2, sample 3.

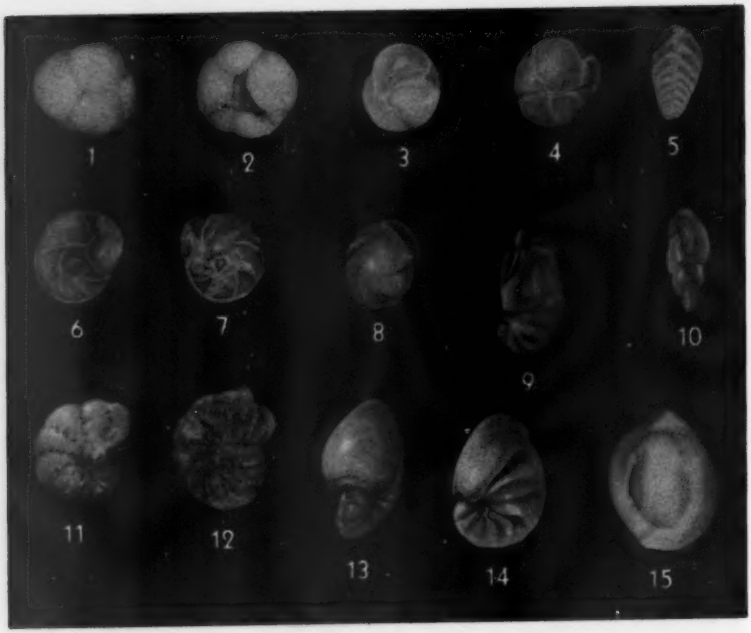
(12) *Globigerinoides rubra* (d'Orbigny). (×60.) Core 11, sample 5.

(14, 15) *Globigerina dubia* Egger. (×60.) (14) dorsal view; (15) ventral view. Core 11, sample 1.

(16, 17) *Globigerinoides sacculifera* (H. B. Brady). (×60.) (16) a specimen showing the projected last chamber; (17) side view of a specimen without the projected last chamber. Core 2, sample 2.



SPECIES TYPICAL OF WARM-WATER SAMPLES



SPECIES TYPICAL OF ARCTIC SAMPLES

PLATE 2

Figure — SPECIES TYPICAL OF ARCTIC SAMPLES

(1, 2) *Globigerina pachyderma* (Ehrenberg). (×72.) (1) dorsal view; (2) ventral view. Core 3-38, sample 3.

(3, 4) *Cassidulina subglobosa* H. B. Brady. (×90.) Showing opposite sides. Core 7, sample 5.

(5) *Bolivina* sp. 1. (×90.) Core 2, sample 2.

(6, 7, 8) *Cassidulina laevigata* d'Orbigny. (×62.) (6, 7) opposite sides of a flange-keeled form; (8) usual form referred to this species. Core 11, sample 4.

(9) *Cassidulinoides bradyi* (Norman). (×90.) Core 9-38, sample 3.

(10) *Virgulina* cf. *squammosa* d'Orbigny. (×100.) Core 2, sample 2.

(11) *Elphidium* sp. (×54.) Core 11, sample 5.

(12) *Elphidium advenum* var. *margaritaceum* (Cushman). (×68.) Core 11, sample 3.

(13, 14) *Nonion labradoricum* (Dawson). (×62.) (13) peripheral view; (14) side view. Core 3-38, sample 3.

(15) *Quinqueloculina seminulum* (Linnaeus). (×68.) Core 15-38, sample 3.

PLATE 3

SPECIES OCCURRING COMMONLY IN BOTH WARM-WATER AND ARCTIC FAUNAS

Figure

(1, 2) *Cibicides pseudoungeriana* (Cushman). (×62.) (1) dorsal view; (2) ventral view. Core 6-38, sample 1.

(3,4) *Nonion pompiloides* (Fichtel and Moll). (×65.) (3) side view; (4) apertural view. Core 11, sample 5.

(5, 6) *Uvigerina peregrina* Cushman. (×60.) Core 3-38, sample 1.

(7, 8) *Nonion* cf. *grateloupi* (D'Orbigny). (×100.) (7) side view; (8) apertural view. Core 2, sample 1.

(9) *Virgulina schreibersiana* Czyzek. (×66.) Side view. Core 1, sample 1.

(10, 11) *Angulogerina angulosa* (Williamson). (×66.) Core 11, sample 5.

(12, 13, 14) *Angulogerina* sp. 1. Core 1-38, sample 1.

(15, 16) *Globigerina bulloides* d'Orbigny. (×72.) (15) ventral view; (16) dorsal view. Core 11, sample 1.

(17) *Buliminella elegans* var. *exilis* (H. B. Brady). (×60.) Core 2, sample 1.

(18, 19) *Globigerina inflata* d'Orbigny. (×60.) (18) ventral view; (19) dorsal view. Core 3-38, sample 1.

(20) *Pyrgo subsphaerica* d'Orbigny. (×44.) Core 11, sample 5.

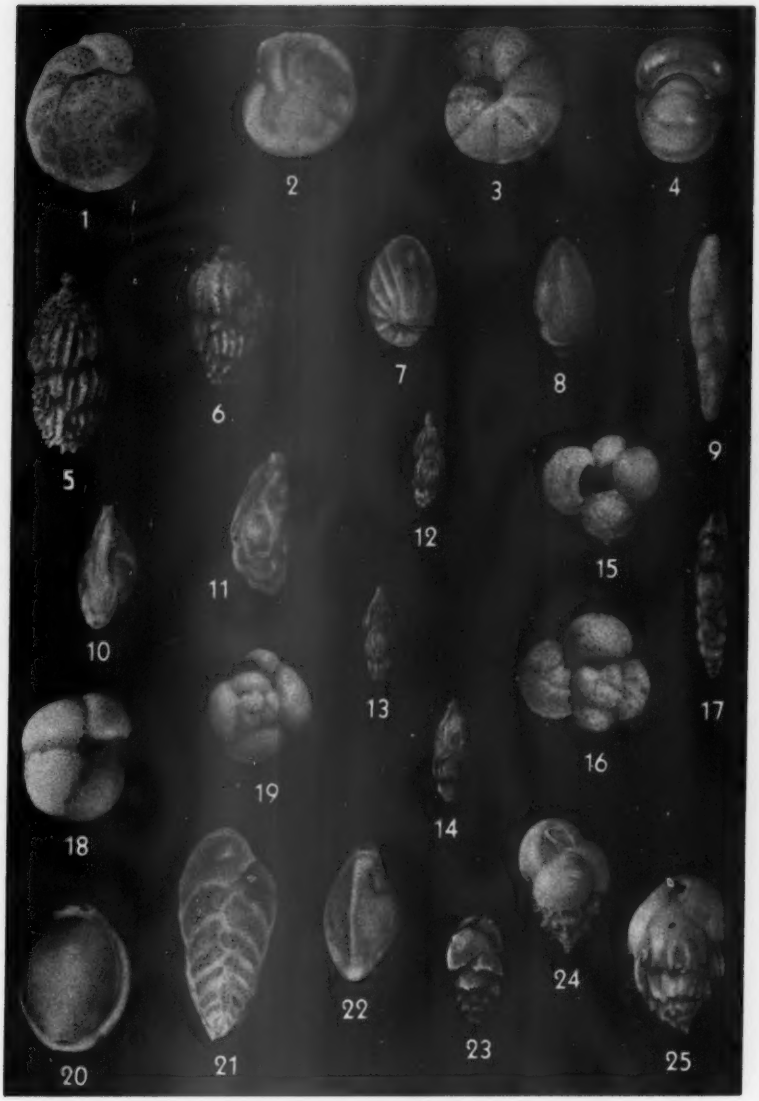
(21) *Bolivina subaenariensis* Cushman. (×50.) Core 4, sample 3.

(22) *Triloculina tricarinata* d'Orbigny. (×68.) Core 11, sample 5.

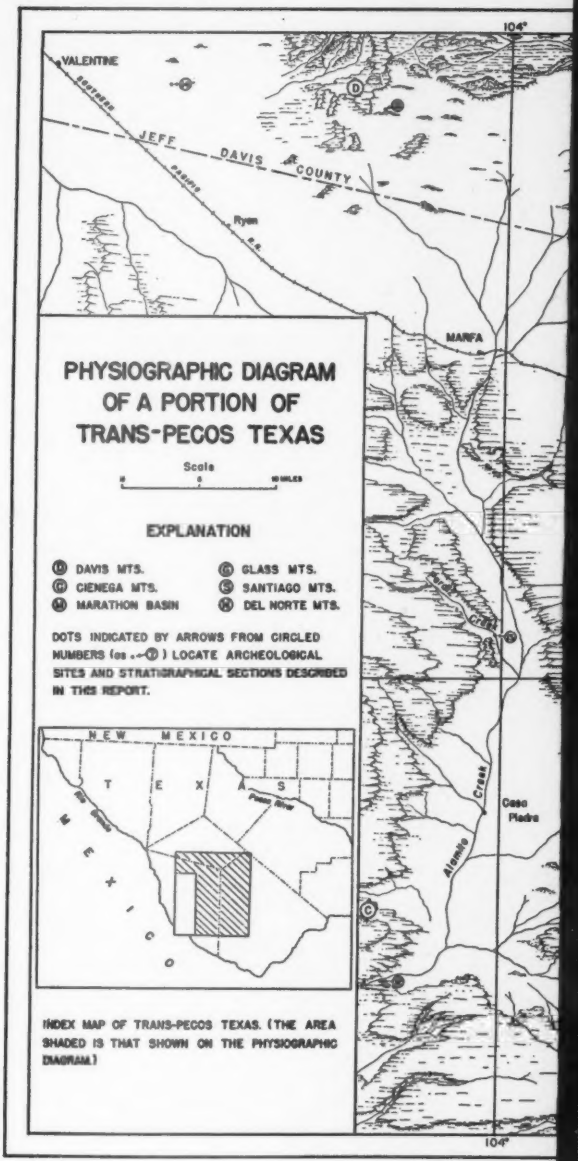
(23) *Bulimina marginata* d'Orbigny. (×72.) Core 9-38, sample 1.

(24) *Bulimina aculeata* d'Orbigny. (×54.) Core 11, sample 5.

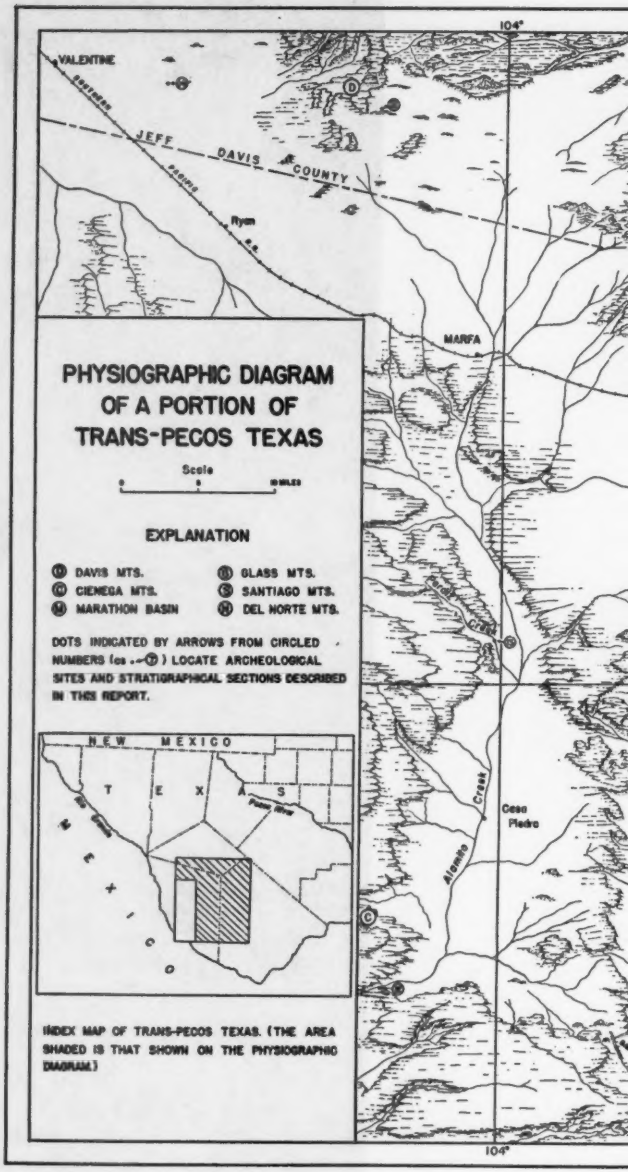
(25) *Bulimina* cf. *inflata* Sequenza. (×58.) Core 11, sample 5.



SPECIES OCCURRING COMMONLY IN BOTH WARM-WATER AND ARCTIC FAUNAS


104°
VALENTINE
JEFF DAVIS COUNTY
Ryan
MARFA
PHYSIOGRAPHIC DIAGRAM
OF A PORTION OF
TRANS-PECOS TEXAS
Scale
EXPLANATION
D DAVIS MTS.
G GLASS MTS.
C CIENEGA MTS.
S SANTIAGO MTS.
M MARATHON BASIN
N DEL NORTE MTS.
DOTS INDICATED BY ARROWS FROM CIRCLED NUMBERS (as ←①) LOCATE ARCHEOLOGICAL SITES AND STRATIGRAPHICAL SECTIONS DESCRIBED IN THIS REPORT.
NEW MEXICO
T E X A S
MEXICO
Rio Grande
Pecos River
Alamito Creek
Casa Piedra
INDEX MAP OF TRANS-PECOS TEXAS. (THE AREA SHADED IS THAT SHOWN ON THE PHYSIOGRAPHIC DIAGRAM.)
104°

PHYSIOGRAP



PHYSIOGRAPHIC D

RAPHIC DIAGRAM

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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QUATERNARY STRATIGRAPHY IN THE DAVIS MOUNTAINS, TRANS-PECOS TEXAS

BY CLAUDE C. ALBRITTON, JR., AND KIRK BRYAN

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ABSTRACT

Quaternary alluvium in valley flats of the Davis Mountains and adjoining lowlands in Trans-Pecos Texas contains remains of extinct horse and mammoth species as well as artifacts and other cultural material. On the basis of disconformities within the valley-fill complex, the Quaternary has been divided into three formations: Neville, Calamity, and Kokernot, in order from oldest to youngest.

The Neville consists mostly of reddish-brown to buff clay and silt. The Calamity contains relatively more sand and gravel than the Neville, although dark zones of humic silt and clay are characteristic of the Calamity. The Kokernot consists of incoherent silt, sand, and gravel. Caliche concretions and cement, abundant in the Neville, are uncommon in the Calamity and generally absent in the Kokernot.

Only the Neville contains mammoth remains. To date, no artifacts have been found in the Neville, although the overlying Calamity formation contains artifacts, buried hearths, and human skeletons. Of several cultures represented in the Calamity, one is Pecos River Cave Dweller. The Kokernot formation contains cultural material at top and bottom; pottery in upper layers shows that these beds were deposited within the interval 1100-1400 A. D.

INTRODUCTION

The recent work of the Peabody-Sul Ross Archeological Expedition provided an excellent opportunity to study the Quaternary stratigraphy of the southern portion of the Davis Mountains and outlying country to the west, south, and east in Trans-Pecos Texas. One of the main purposes of the archeological investigation was the exploration of sites deeply buried in alluvium. Accordingly, the writers studied the sections revealed in the walls of excavations and, by comparing these with natural sections along streams, were able, in cooperation with the archeologists, to establish a succession of formations as well as the sequence of major physical events in the Quaternary history.

The sites jointly selected by the archeologists and geologists as most important for comparative study are scattered over an area of about 3500 square miles. This area is part of the Mexican Highlands Province (King, 1937, p. 4) and is dominated by dissected plateaus, mesas, and cuestas separated by broad flat valleys (Pl. 1). The climate is semiarid

to arid, and the average annual rainfall ranges from 17 inches in the higher mountains to 10 inches or less in the lowlands. Half or more of the precipitation falls as torrential showers during the summer months. Most streams of the area are ephemeral or intermittent, although some of the larger ones heading in the mountains flow the year round. The precise location and general configuration of the area over which the geological investigation was made are shown on the physiographic diagram (Pl. 1). Geographic descriptions to supplement the diagram are given in the descriptions of special areas.

In this report emphasis is placed on the stratigraphy and historical geology of the Quaternary. Archeological data are introduced only where they are necessary for correlation of formations, dating of physical events, or interpretation of conditions of sedimentation. As a result, not all the cultural complexes discovered by the archeologists are mentioned in this paper. A full account of the archeology is being prepared by Mr. T. N. Campbell and Mr. J. C. Kelley, who have generously provided a summary of their findings to aid in writing this report.

ACKNOWLEDGMENTS

Field work, done in the summer of 1938, was made possible by a grant from the Penrose Bequest of the Geological Society of America. Surveying and drafting equipment for collecting field data and preparing this report were supplied by Professor E. W. Shuler, of Southern Methodist University. Mr. Samuel Vaughan assisted for several weeks. Mr. C. C. Albritton, Sr., who was a constant co-worker and companion, loaned a car for use in the field.

Without the friendly co-operation of Mr. J. C. Kelley, of Sul Ross State Teachers College, and Mr. T. N. Campbell, of the University of Texas, the archeological and geological findings could not have been correlated.

Gastropods were identified for this report by Professor E. P. Cheatum, of Southern Methodist University. Professor A. S. Romer, of Harvard University, identified mammoth teeth loaned by the Museum at Sul Ross College through the courtesy of Professor V. J. Smith and Mr. Kelley.

GENERAL STRATIGRAPHY

Quaternary deposits in the valley flats of the southern Davis Mountains and vicinity consist of three bodies of alluvium separated by disconformities. The oldest alluvial fill—the Neville formation—rests unconformably on bedrock. The intermediate fill, or Calamity formation, occupies channel depressions which were cut in the Neville after that formation had been deposited and deeply weathered. The youngest body

FIGURE 1. CROSSEN MESA (LEFT) AND ELEPHANT MOUNTAIN (RIGHT)
Viewed from south along Terlingua-Alpine road in Green Valley.

FIGURE 2. CUESTAS ALONG DAVIS MOUNTAIN FRONT
Viewed toward west along northern margin of Green Valley south of Elephant Mountain.

FIGURE 3. ELEPHANT MOUNTAIN
Viewed northward up bed of Calamity Creek. White rocks in right foreground and along right and left skylines are Cretaceous limestones.

FIGURE 1. DISTRIBUTARIES OF CALAMITY CREEK (UPPER SEGMENT)
Viewed toward northwest from southern slopes of Elephant Mountain.

FIGURE 2. SOUTHERN PORTION OF VALLEY
Viewed from Elephant Mountain. Barren strip in foreground is distributary area for upper segment of Calamity Creek.

FIGURE 3. NORTHWESTERN RE-ENTRANT OF VALLEY AT ENTRANCE OF SHEEP CREEK
Viewed northward from eastern margin of Crossen Mesa.

of alluvium—Kokernot formation—fills channels which were excavated in the Calamity and Neville formations after the Calamity had been deposited. In places thin floodplain deposits, belonging to the Kokernot, overlap older bodies of alluvium.

The Neville contains more clay and more secondary calcium carbonate than either the Calamity or the Kokernot. It is the only formation that contains remains of mammoths.

Of the various materials in the Calamity formation, the most characteristic are beds of dark humic clay and silt, which commonly contain hearths. From the Calamity the archeologists took artifacts of several types, including points of Pecos River Cave Dweller design (Sayles, 1935, pl. 18).

The Kokernot consists of incoherent beds which are mostly silt, sand, and gravel. This formation contains abundant artifacts, including El Paso polychrome pottery.

In designating these three formations the terms Pleistocene and Recent have been avoided. Quaternary, though a broader term, is preferred because it is less likely to confuse those who think of Pleistocene and Recent in terms of a glacial chronology which cannot be applied to Trans-Pecos Texas at present.

ELEPHANT MOUNTAIN AREA

SKETCH OF THE GEOGRAPHY AND GEOLOGY

Southern front of Davis Mountain upland.—Along their southern front the Davis Mountains are essentially a group of mesas and cuestas formed by dissection of stratified volcanic and sedimentary rocks. Among the more imposing landmarks is Elephant Mountain, which stands at the southeastern corner of the Davis Mountain upland (Pl. 1; Pl. 2, figs. 1, 3). A few miles south of the thirtieth parallel this upland ends along an escarpment which trends in an easterly direction. To the south lies Green Valley, a lowland about 30 miles square (Pl. 1; Pl. 2, figs. 1, 2). Relief along the boundary between Green Valley and the Davis Mountains ranges to slightly more than 2000 feet.

Lowland wedges indent the Davis Mountain front wherever mountain streams enter Green Valley. One of the larger valley re-entrants, lying east and south of Elephant Mountain, is drained by Calamity Creek and its tributaries, chief among which is Sheep Creek. Hereafter this will be called the Calamity-Sheep Creek Valley.

Calamity-Sheep Creek Valley.—South of Neville's ranch-house this valley lies between Elephant Mountain and Crossen Mesa (Fig. 1). Its width near the southern end of Elephant Mountain approximates 3 miles. Southward the valley spreads laterally to include lowland slopes along

the southern margins of its bounding mesas. These flats are separated from Green Valley by a low southward-facing cuesta breached by the alluvial flat of Calamity Creek (Pl. 2, figs. 2, 3).

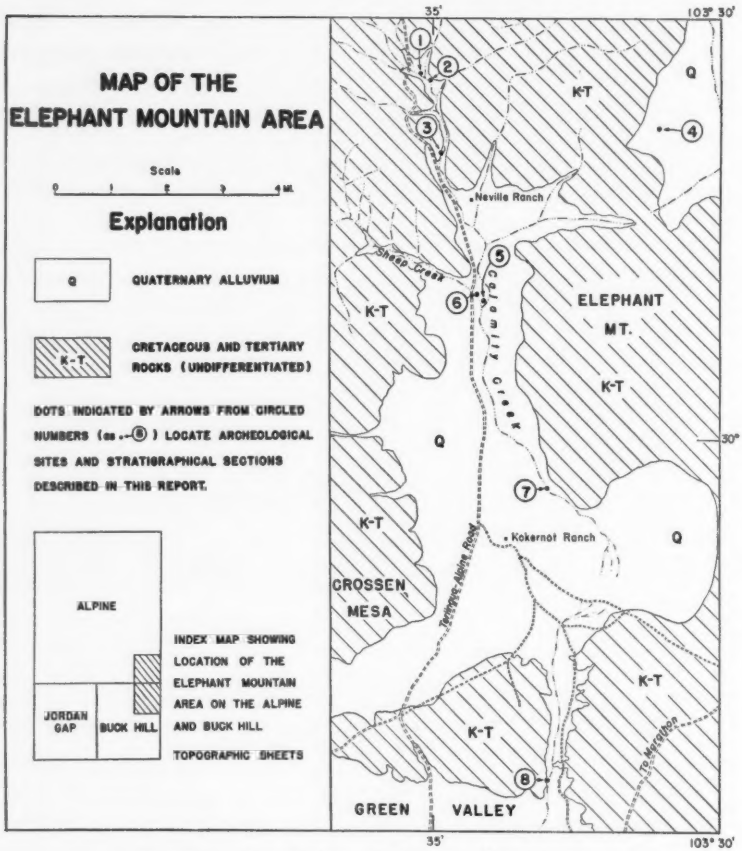

FIGURE 1.—*Areal geology of Elephant Mountain area*

From the side of Elephant Mountain or Crossen Mesa the Calamity-Sheep Creek Valley appears to be an almost featureless brush-covered plain whose margins merge with talus slopes of the bordering mountains (Pl. 3). In detail, however, the flat is diversified by arroyo trenches, by low gravel ridges bordering the arroyos, and by gravel-capped spurs slanting down toward Calamity Creek along the base of Crossen Mesa.

These spurs preserve remnants of a pediment which was dissected before the present valley flat was formed.

The flat is drained by Calamity Creek, an ephemeral stream named in commemoration of its sudden and destructive floods. Its course is discontinuous, consisting of three segments. The upper or northern segment, about 20 miles long, ends near the southern slopes of Elephant Mountain. Here the arroyo banks disappear, so that unconfined floodwaters spread over an area of several square miles (Pl. 3, figs. 1, 2). During exceptionally high floods the distributed water flows southward into headwater tributaries of an intermediate channel segment. The latter is the shortest of the three, extending only a mile beyond the cuesta at the northern margin of Green Valley. At the end of this segment floodwaters again spread over the flats, a portion of the runoff entering the Terlingua drainage to the west, the remainder following a third section of the Calamity channel into the Maravillas system (Pl. 1). The intermediate and lower divisions of Calamity Creek are extending their courses headward, tending to form a continuous channelway.

Bedrock.—Quaternary deposits of the Calamity-Sheep Creek Valley rest unconformably on Cretaceous and Tertiary rocks. Cretaceous strata consist of sandstone, sandy shale, and limestone, exposures of which may be seen along Sheep Creek and around the base of Elephant Mountain. Cretaceous limestone forms the cuesta at the southern end of the Valley (Pl. 2, figs. 2, 3).

Tuff, agglomerate, and lava of Tertiary age compose the upper slopes of Crossen and Elephant mesas, which are capped by thick layers of columnar trachyte (Baker and Bowman, 1917, p. 129).

Cretaceous and Tertiary rocks of the area have a low regional dip to the north. Locally the rocks are broken by normal strike faults. These displacements do not affect the Quaternary alluvium of the valley flats.

Quaternary rocks.—Local Quaternary deposits include talus, slopewash, and landslide debris of mesa slopes and spurs, and alluvium of the valley flats. Only deposits of the valley flats are described in this report. Their distribution is shown in Figure 1. The deposits consist of stream-laid materials ranging in size from clay particles to boulders. Prevailing colors are dull hues intermediate between orange and yellow. Where bedrock is exposed in arroyos the thickness of the alluvium may be as much as 30 feet, although accounts of wells dug near Kokernot's house suggest that in places the thickness reaches 50 feet. Alluvium shows no evidence of having been faulted, warped, or greatly compacted since its deposition.

Although the valley flat is unterraced, sections along Sheep and Calamity channels reveal that it is composed of three alluvial formations.

NEVILLE FORMATION

Name and type locality.—The Neville, oldest of the three Quaternary formations, is named for a type locality on the west bank of Calamity

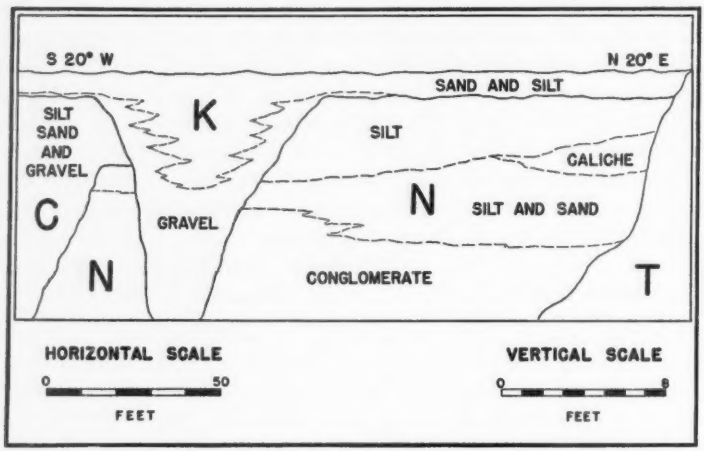

FIGURE 2.—*Section at type locality of Neville and Kokernot formations*

K—Kokernot formation
C—Calamity formation
N—Neville formation
T—Tertiary bedrock

Interformational contacts—solid lines
Intraformational contacts—broken lines

Creek one mile northwest of Neville's ranch-house (Fig. 1, loc. 3). Here the formation is exposed for about 70 yards along the creek. Northward the Neville abuts against Tertiary igneous rock whereas to the south it is intersected by younger alluvium (Fig. 2).

Exposures.—In addition to the type locality, good exposures occur along the lower banks of Calamity and Sheep creeks near their junction, along the east bank of Calamity Creek near the southern end of Elephant Mountain (Fig. 1, loc. 7), and in the beds of small arroyos northeast of Elephant Mountain (Fig. 1, loc. 4). Artificial exposures may be seen in a ditch paralleling the west side of the Alpine-Terlingua road south of the crossing over Sheep Creek. Throughout most of the Elephant Mountain area, however, the Neville is concealed by younger alluvium.

Lithology.—At the type locality the Neville consists of calcareous silt and conglomerate. (*See* stratigraphical section 1.) The materials are

poorly sorted; silty beds contain appreciable quantities of clay, sand, pebbles, and cobbles, and the phenoclasts of conglomerates are set in a matrix of silty sandstone. All the rocks at this locality have large amounts of secondary calcium carbonate, diffused as caliche and in the form of white nodules. In places the caliche forms thick crusts in the finer beds (Pl. 4, fig. 1). This same material encrusts pebbles and cobbles scattered through the silts, and binds the sandy matrix of the conglomerate.

Near the junction of Calamity and Sheep creeks the Neville crops out along the base of arroyo banks (Pl. 6, fig. 2) as a reddish-brown ferruginous and calcareous silty clay. (*See* stratigraphical sections 3 and 5.) Interbeds of sand and gravel occur in places, but most of the formation is fine-grained and massive. As at the type locality there is much caliche. Nodules up to an inch across are embedded in silty clay along the north bank of Sheep Creek 75 feet above its intersection with Calamity. Elsewhere in this general area caliche is not so conspicuous, although all Neville samples collected reacted briskly with hydrochloric acid. A considerable portion of the caliche seems concentrated in whitish films lining minute tubular openings in the silty clay. Some of the openings are worm borings; others appear to be rootlet molds.

The Neville is well exposed for 75 feet along the east bank of Calamity Creek near the southern end of Elephant Mountain (Fig. 1, loc. 7). The beds are of reddish-brown clayey and silty sand with scattered pebbles. Caliche nodules averaging half an inch in diameter give the sediments a mottled appearance.

Similar deposits exposed in the ditch on the west side of the Alpine-Terlingua road 0.7 mile south of the Sheep Creek crossing contain unusually large and abundant caliche nodules in the form of vertical cylinders. Some, up to half a foot long, fill root molds.

In the alluvial flat northeast of Elephant Mountain, the Neville is exposed along banks of shallow discontinuous arroyos trending east. At locality 4 of Figure 1 the formation consists of pinkish silty clay with interbedded pebble and cobble conglomerate. Small calcareous nodules weather from the silty clay (Pl. 4, fig. 2). Caliche encrusts the pebbles and cobbles and cements the sandy matrix of the conglomerate. Cobbles in the conglomerate are mostly of volcanic rock, with admixed limestone fragments. Phenoclasts are only superficially weathered, volcanic fragments showing fresh surfaces when broken.

Thickness.—At the type locality the Neville is 11 feet thick. That the formation may be thicker in other parts of the Calamity-Sheep Creek Valley is suggested by accounts of water wells dug in the alluvial flat near the Neville and Kokernot ranch-houses. According to the respective owners, these wells obtain water from gravel at a depth of 50 feet.

Fossils.—J. C. Kelley has taken elephant tusks from the Neville at two localities in this area. A broken tusk was dug from calcareous pebbly silt at the type locality on Calamity Creek. (*See* stratigraphical section 1, unit 2.) Small tusk slivers are still to be found in this bed. Another tusk fragment, taken from conglomeratic silty clay at locality 4 of Figure 1, is preserved in the Museum at Sul Ross College, Alpine. According to Kelley, nothing about the occurrence of tusks at either locality suggested that they belonged to articulated skeletons. Apparently they had been strewn along stream channels and buried during the deposition of the Neville beds.

Small fragile shells of fresh-water and terrestrial molluscs are locally abundant in the Neville formation. The following species were identified by Professor E. P. Cheatum from samples collected at the type locality. (*See* stratigraphical section 1, unit 2.)

Pelecypoda
- * *Pisidium compressum* Prime (?)

Gastropoda

Fresh-water shells
- * *Gyraulus carus* Pilsbry and Ferriss
- †* *Physa anatina* Lea
- *Galba obrussa* (Say)

Land shells
- *Discus patulus* (Deshayes)
- *Gastrocopta contracta* (Say)
- *G. procera duplicata* (Sterki)
- *Vertigo ovata* Say
- * *Succinea grosvernori* Lea
- * *S. luteola* Gould

* Found also in Calamity formation.
† Reported living in Davis Mountain area.

According to Professor Cheatum, all species listed above are extant, although only one, *Physa anatina* Lea, has been reported living in the Davis Mountains at the present time (Cheatum, 1935, p. 3).

Although archeological excavations along Calamity Creek penetrated the Neville formation at several localities, and natural exposures along Sheep and Calamity creeks were closely examined by the archeologists, no remains of human cultures were found in the formation. Elsewhere in Texas and New Mexico it has been shown that man was contemporaneous with the mammoth (Sellards, 1938; Ray and Bryan, 1938; Roberts, 1937, p. 157), so remains of ancient cultures may some day be discovered in the Neville.

Conditions of origin.—The Neville formation, containing bones of land mammals and shells of fresh-water and land molluscs, has a linear dis-

FIGURE 1. TYPE LOCALITY OF NEVILLE FORMATION
Neville forms all but upper foot of bank behind man.

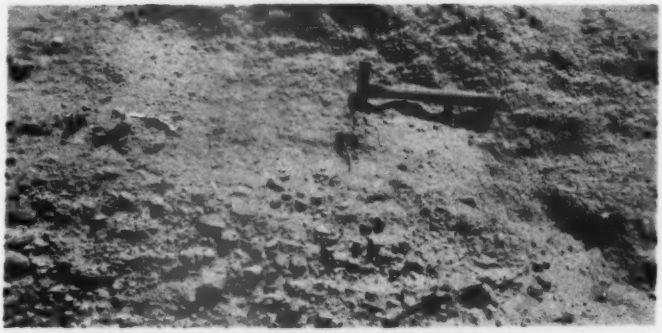

FIGURE 2. NEVILLE FORMATION AT LOCALITY 4
Caliche nodules weathering from silty clay at end of knife blade.

FIGURE 3. CALAMITY FORMATION AT TYPE LOCALITY ON SHEEP CREEK

NEVILLE AND CALAMITY FORMATIONS

FIGURE 1. CALAMITY FORMATION ALONG INTERMEDIATE SEGMENT OF CALAMITY CREEK
Cretaceous limestone at right.

FIGURE 2. NEVILLE-CALAMITY CONTACT NEAR JUNCTION OF SHEEP AND CALAMITY CREEKS
White cobble in lower Calamity beds is a grinding-stone.

FIGURE 3. ALLUVIUM ALONG MARAVILLAS CREEK ABOVE ROCK HOUSE GAP

ALLUVIUM ALONG CALAMITY AND MARAVILLAS CREEKS

tribution along the Calamity Valley. Conglomerate lentils in the silty clays are composed of stream-worn pebbles and cobbles; fine-grained deposits are ramified by root canals. These facts indicate that beds here described are of fluvial origin.

That conglomerate lentils in the formation are relatively thin and grade vertically into fine silty clay may be taken to indicate that streams which deposited the Neville shifted their courses from time to time over the valley flat. Silty clays evidently represent slack-water, floodplain deposits, which probably interfinger marginally with coarser slopewash from the surrounding mountains.

Abundance of root canals in the Neville silty clay indicates that vegetation covered the valley flats during deposition of the formation. Yet little organic matter has been preserved as humus. Evidently carbonaceous materials were oxidized and decomposed as rapidly as they tended to accumulate. This suggests that the Neville beds were deposited in an environment where relatively high temperatures, a sufficiency of moisture for microbiological activities, and aeration of the sediments acted jointly to destroy organic matter (Robinson, 1937, p. 153) and to keep iron compounds oxidized so as to form reddish pigmenting materials (Twenhofel, 1932, p. 777-778).

Cracks filled with illuvial clay are abundant in the Neville (Pl. 6, fig. 1). Many of the cracks were opened and filled before the Calamity formation was deposited, but it is not known whether this took place during or following deposition of the Neville. The clastic veins indicate that the clays expanded and contracted repeatedly under alternating wet and dry conditions. If it could be shown that some of the fillings were formed before the close of Neville sedimentation, this would suggest that the formation was deposited under a climatic régime in which there was seasonal concentration of rainfall.

Insofar as general climatic conditions may be inferred from the sediments, the Neville could have been deposited under semiarid conditions similar to those which now obtain in this area. On the other hand, Quaternary land molluscs have been regarded as good indicators of general climate (Baker, 1937, p. 69-72), so that the apparent difference between Neville and living faunules in the Davis Mountains may signify environmental change since Neville time. Of six species of land snails reported from the Neville, two were also found in the Calamity formation, but none has been reported living in the Davis Mountain area. However, any inferences that might be drawn from this would be unreliable, for molluscs of the region, living or embedded in alluvium, have not been sufficiently studied to warrant generalizations on their stratigraphical ranges or geographical distributions.

In summary the Neville formation appears to have been deposited by shallow streams which shifted their courses across the Calamity-Sheep Creek Valley during the work of aggradation. Pools occupying local depressions along stream channels accommodated *Physa, Pisidium,* and other small fresh-water molluscs. Sedimentation in the valley flat did not proceed so rapidly as to prevent growth of small plants, which must have been sufficiently luxuriant to support, among other herbivorous animals of that time, the mammoth.

CALAMITY FORMATION

Type locality and exposures.—The type locality of the Calamity formation is along the east bank of Sheep Creek, directly south of the Terlingua-Alpine road crossing (Fig. 1, loc. 6). The formation is well exposed along the banks of Sheep Creek, along Calamity Creek from Neville's house to the southern end of Elephant Mountain, and along the intermediate segment of Calamity Creek.

Lithology.—At the type locality the Calamity consists of silt and sand with interbedded gravel and subordinate amounts of silty, humic clay (Fig. 3; Pl. 4, fig. 3). A foot of pebble and cobble gravel composed of subrounded fragments of Cretaceous limestone and Tertiary volcanic rocks marks the base of the section. This grades upward into 4 feet of pebbly, clayey silt and sand whose upper half is dark with humus. The upper part of the section is essentially a duplication of the sequence already described, with a second, somewhat darker, humic zone at the top. (*See* stratigraphical section 4.)

Along the north bank of Sheep Creek a short distance above the intersection with Calamity Creek, both upper and lower contacts of the formation may be seen (Pl. 6, fig. 2). Here the lower part consists of alternating thin beds of clayey silt and fine sand, with lentils of grit and pebble gravel. Unlike the section at the type locality, there is no lower humic zone, although the upper one persists in the upper 4 to 5 feet. (*See* stratigraphical section 5.)

At locality 5 of Figure 1, the Calamity is well exposed along the north bank of a short arroyo connecting one of the larger archeological excavations with Calamity Creek (Fig. 4). A thin bed of fine sand, marked by a ledge in the otherwise steep bank, divides the sequence into two similar halves, each consisting of clayey silt with a dark humic zone at the top. (*See* stratigraphical section 3.) Humus is not uniformly distributed throughout the darkened zones; there are alternating darker and lighter thin beds. In places, as along the east bank of Calamity Creek across from locality 5, the dark zones lose their identity among numerous discontinuous gray lamellae distributed throughout the section.

The Calamity is well exposed at localities 1 and 2 of Figure 1. At locality 1 the greater part of the section consists of massive brownish calcareous silty and clayey sand with interbedded gravel. A foot of compact humic silt with crude rectangular jointing caps the section. A

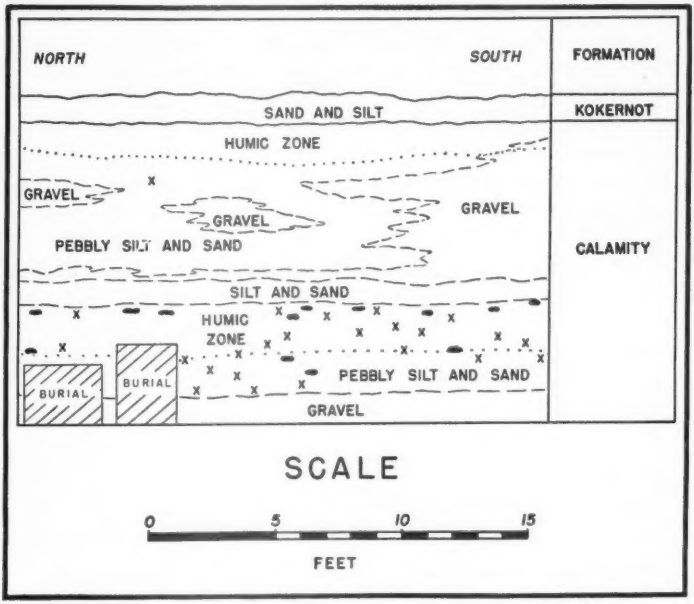

FIGURE 3.—*Section at type locality of Calamity formation*

X—horizon at which artifact was found
—•—horizon at which hearthstone was found
Interformational contacts—solid lines
Intraformational contacts—broken lines
Bottom of humic zones—dotted lines

less complete sequence at locality 2 is similar, although the lower sands and silts are more gravelly. (*See* stratigraphical section 2.)

Near the southern end of Elephant Mountain (Fig. 1, loc. 7) the oldest beds in the formation are of boulder and cobble gravel. The gravel grades upward into sandy and clayey silt with scattered pebbles and gravel lentils. At the top is a humic zone of variable thickness. (*See* stratigraphical section 6.) This section is particularly instructive as it shows within a relatively short distance all three alluvial formations together with underlying bedrock (Fig. 5).

The formation is well exposed along the intermediate segment of Calamity Creek (Pl. 5, fig. 1). At locality 8 it consists mostly of calca-

reous sandy and clayey silt, as shown in stratigraphical section 7. Gravel lentils are common in the basal layers, and three dark humic zones may be distinguished in the upper 5 feet.

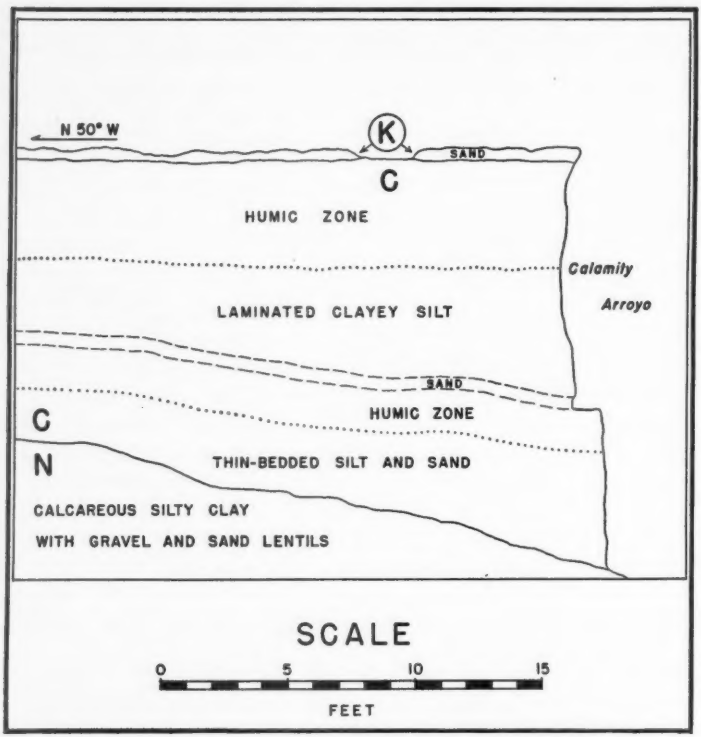

FIGURE 4.—*Section exposed in tributary arroyo at locality 6*

K—Kokernot formation
C—Calamity formation
N—Neville formation

Interformational contacts—solid lines
Intraformational contacts—broken lines
Bottom of humic zones—dotted lines

Thickness.—At the type locality the Calamity is 11.5 feet thick. Elsewhere along Sheep Creek and the upper segment of Calamity Creek exposed thicknesses range from 12 to 16 feet. The formation has a maximum exposed thickness of 30 feet, measured along the intermediate segment of Calamity Creek at locality 8.

Relationships to underlying rocks.—The Calamity rests disconformably on the Neville formation (Pl. 5, fig. 2; Pl. 6, fig. 2). The Neville-Calamity contact is generally undulatory and in many places is marked

by a concentration of coarse clastic materials in basal beds of the younger formation (Pl. 6, fig. 1).

Where a small side-arroyo enters Calamity Creek at locality 5 the basal Calamity contact may be seen to slant upward toward the west away from the west bank of the creek (Fig. 4). Likewise the contact rises eastward away from the east bank opposite this locality, as revealed by sections observed in archeological test-pits (Fig. 6). Thus it is evident that along Calamity Creek above its intersection with Sheep Creek the Calamity formation fills a valley cut in the Neville. Inclination of the basal Calamity contact, as revealed in natural and artificial exposures, indicates that the old valley was approximately 100 yards wide, or about four times the average width of the present Calamity arroyo in this area. Cut in coherent clayey beds of the Neville, the valley was more open and flaring than its modern counterpart, which has steep, almost vertical walls. However, the deepest portion of the post-Neville, pre-Calamity valley was essentially coincident with the course of the present creek, as indicated by the fact that thickest portions of the Calamity formation occur nearest the bed of the creek. Tributaries of Calamity and Sheep creeks are few and short, so that transverse sections of the Calamity formation were observed only within the area already mentioned.

Along the Alpine-Terlingua road, a few hundred yards south of the crossing over Sheep Creek, the Neville is exposed in drainage ditches. Here the upper surface of the Neville lies only about a foot below the level of the valley flat, and the Calamity is apparently absent. It would appear that the Calamity formation is restricted to concavities of old channelways whose axes are marked by the present courses of Calamity and Sheep creeks.

Organic remains.—Materials of organic origin in the Calamity include humus, charcoal, shells of aquatic and land molluscs, and human skeletons. Root canals and worm burrows are characteristic of the finer beds, particularly those that contain humus.

Humus is not uniformly distributed through the formation but is generally concentrated in zones as much as 5 feet thick. In section these appear as horizontal dark bands, which, although conspicuously dark, actually contain little humus. Crude ignition analyses of sediments collected along Sheep Creek indicate that carbonaceous material composes 1 per cent or less by weight of the darkest samples. With few exceptions, however, the humic zones are also calcareous, and Robinson (1937, p. 152) has noted that unusually dark humus may be produced in the presence of calcium carbonate.

Not uncommonly associated with the humic sediments, though by no

means confined to them, are bits of wood-charcoal up to an inch across. Some, occurring as small discontinuous lentils in silt or sand, may record forest or grass fires. Much of the charcoal, however, is concentrated about buried hearths and reworked hearthstone.

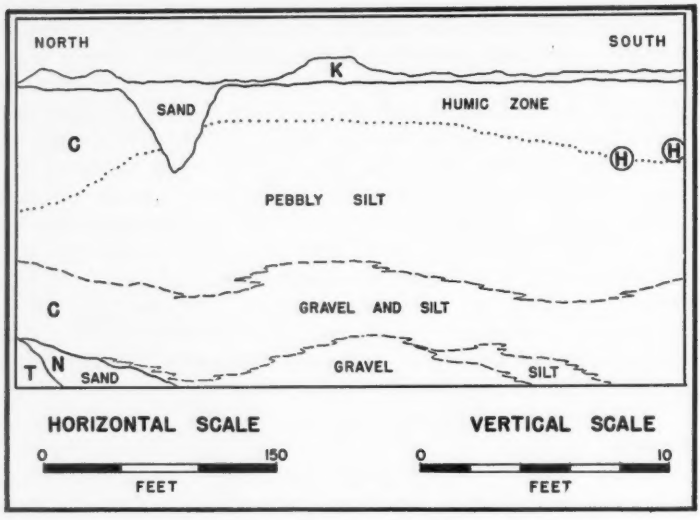

FIGURE 5.—*Section at locality 7*

K—Kokernot formation
C—Calamity formation
N—Neville formation
T—Bedrock
Ⓗ—levels at which hearths were found

Interformational contacts—solid lines
Intraformational contacts—broken lines
Bottom of humic zone—dotted lines

Shells of aquatic and terrestrial molluscs are embedded in silt and sand of the Calamity formation. The following species were identified by Professor Cheatum.

Pelecypoda
* *Pisidium compressum* Prime (?)
Gastropoda
Fresh-water shells
Helisoma trivolvis lentum (Say)
H. tenue (Phillipsi)
* *Gyralus carus* Pilsbry and Ferriss
† * *Physa anatina* Lea
Land shells
* *Succinea luteola* Gould
* *S. grosvernori* Lea

* Found also in Neville formation.
† Reported living in Davis Mountain area.

Two human skeletons were exhumed at the type locality. According to T. N. Campbell, who is to describe these burials, the bones were in shallow graves sunk into pebbly silt and sand below the top of the lower humic zone (Fig. 3). Beds above the graves were intact prior

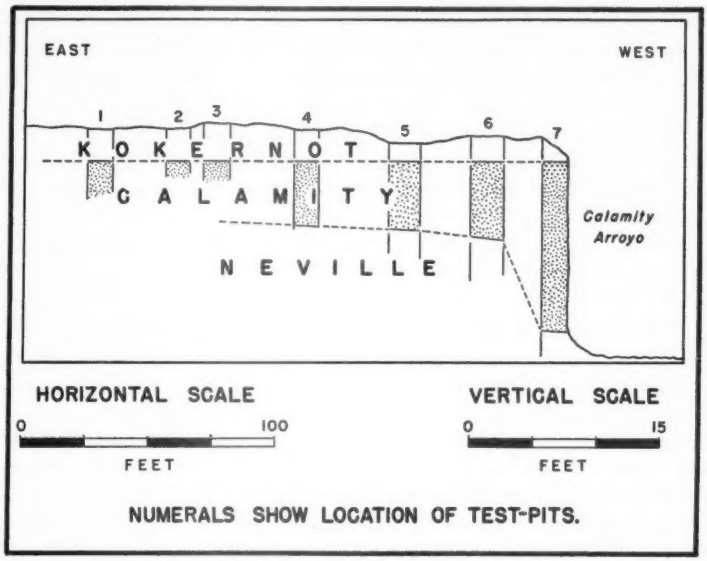

FIGURE 6.—*Rise of Neville-Calamity contact away from Calamity Creek*

to excavation, which proves that interment took place before the upper half of the Calamity formation had been deposited.

Objects associated with human occupation.—On valley flats of the Elephant Mountain area there are many ringlike enclosures or circular pavements of blackened, fire-cracked stones. Association of charred wood, ash, flint chips, artifacts, and camp refuse with these burned rocks proves that they are open hearths marking Indian campsites. Where hearths were located in areas which are now being dissected, they exhibit all stages of integrity, some preserving their circular plan, others disaggregated, with their component stones irregularly scattered or strewn along gullies. Even where hearthstone has been washed from an original site, it can usually be distinguished from similar rocks naturally weathered. Hearths and hearthstones similar to those on the alluvial flats are buried in the Calamity formation.

In the Calamity-Sheep Creek Valley hearthstones occur along the Neville-Calamity contact and in the lower few feet of the Calamity formation (Fig. 3). These charred rocks record the dismantling of campsites during early stages of Calamity sedimentation, although it is not clear from local evidence whether the camps themselves were occupied during deposition of the Calamity. They may have been occupied during the erosional epoch following deposition of the Neville or even during the closing stages of Neville sedimentation (J. C. Kelley, personal communication, June 4, 1939). Intact hearths occur in the upper two-thirds of the Calamity, generally as at localities 2, 7, and 8, in humic zones. Where exposed in section these hearths resemble, on casual inspection, lentils of stream-laid cobbles, for which the geologist may unwittingly mistake them.

Archeological workings in the Calamity at the type locality yielded an assemblage of stone artifacts, including projectile points, blades, scrapers, gravers, choppers, and grinding stones. Most of the artifacts came from within or below the lower humic zone, although a few were found near the top of the section (Fig. 3). Similar objects of human workmanship were found in excavations around locality 5 and at natural exposures along Sheep and Calamity creeks (Pl. 5, fig. 2).

According to J. C. Kelley (personal communication, May 2, 1939) none of the cultural complexes represented by artifacts in the Calamity formation can be accurately dated at present. Some artifacts in the middle of the formation are of Pecos River Cave Dweller aspect, similar to those in a complex the whole of which was tentatively dated by Setzler (1935) around 700 A.D.

Conditions of origin.—The Calamity formation was deposited by streams along flaring channelways cut into the Neville and underlying rocks. Very likely the streams were intermittent or ephemeral, for the valleys afforded campsites during the cycle of aggradation.

Between floods men camped along the bottoms, leaving hearths and other evidence of their occupancy to be buried by the next layer of silt. During pauses in sedimentation, plants flourished in the bottoms, and their residues impregnated the silt with humus. Intervals of equilibrium between the agents of erosion and deposition appear not to have been sufficiently long for development of mature soil profiles. Pauses in alluviation were of sufficient duration, however, to allow accumulation of cultural materials, so that today the humic zones guide archeologists to the most likely places for collecting.

In time the channelways were filled to the level of the surrounding valley flat. Humic zones near the top of the formation record an interval of stability before the next cycle of dissection began.

CLASTIC VEINS IN NEVILLE AND CALAMITY FORMATIONS

Wherever the Neville and Calamity formations contain considerable clay or colloidal organic materials, they are found cut by innumerable veins of clay and silt. These veins, up to 2 inches across, make high angles with bedding planes they intersect, so that in section they appear like small dikes. Some branch irregularly. All have resulted from downward infiltration of clay and silt into tension cracks.

Along arroyo banks near the junction of Sheep and Calamity creeks the veins are well displayed (Pl. 6, fig. 1). Here one may distinguish two sets: one brownish, the other dark gray. Veins of brownish ferruginous clay are restricted to beds of similar color in the Neville and are truncated along the Neville-Calamity contact. Younger gray veins are best developed in the Calamity formation, although some cut across the basal disconformity and extend downward into the Neville, severing or paralleling the older brownish veins. Gray fillings may be traced upward to their sources in humic zones. Many veins of both sets are multiple, having been formed by successive infiltrations of materials into cracks periodically opened.

The presence or absence of alluvial veins, therefore, cannot serve as criteria for determining relative ages of alluvial formations. Their development depends not so much on time as on the nature of the enclosing sediments and on fluctuations in their water content. In this example their presence indicates that since the Neville cycle of sedimentation the alluvium has been alternately wet and dry.

KOKERNOT FORMATION

Exposures and type locality.—The Kokernot is exposed in section at the top of arroyo banks. Over most of the valley flat it forms a thin cover above older alluvial formations (Pl. 6, fig. 2), so that areally it is the most widely exposed of the three. The type locality is the same as that of the Neville (Pl. 1, loc. 3).

Lithology and thickness.—Kokernot formation consists predominantly of uncemented quartz sand and silt with interbedded gravel lentils. In places, as at the type locality, clay is mixed with the silt and sand. (*See* stratigraphical section 1.) Secondary calcium carbonate is generally lacking, and embedded pebbles and cobbles are not crusted with caliche like those in the Neville.

At the type locality the formation varies from less than a foot to 13 feet thick. Along Calamity and Sheep creeks its thickness averages about one foot.

Relationship to underlying rocks.—At the type locality the Kokernot rests disconformably on both the Neville and Calamity formations. Here

the thickest part occupies a narrow channel which was about 12 feet deep prior to filling. Similar channel-fillings were found along the side of Calamity arroyo near the southern end of Elephant Mountain. Between channels the formation blankets older alluvium, on which it rests with undulatory contact.

Age.—The archeologists were able to show that several campsites exposed on the surface of the valley flat had weathered from upper layers of the Kokernot. Excavations in the upper few inches near locality 5 revealed intact hearths with associated stone implements and pottery. From a consideration of the entire cultural complex, J. C. Kelley (Personal communication, April 29, 1939) has estimated that local sites in the Kokernot were occupied within the fifteenth or sixteenth centuries A.D. This accords with more conclusive archeological evidence presented later in indicating that some of the upper beds in the formation were deposited only a few centuries ago.

Conditions of origin.—That the Kokernot contains lentils of rounded cobbles and locally fills channels evinces its fluvial origin. Where the formation occupies channel depressions, these appear to intersect the present arroyos nearly at right angles. Bottoms of the filled channels lie at or a few feet above present arroyo beds, so that it would seem they represent old tributaries to former trenches comparable in depth and almost identical in position with drainageways of Sheep and Calamity creeks. Presumably the former trenches, like their tributaries, were filled with the Kokernot prior to the present cycle of channeling. When, during the Kokernot cycle of deposition, the old channels had been filled to near the level of the former valley flat, thin floodplain deposits were distributed away from the axes of the valleys, building the flats to a grade about a foot higher than their position at the close of the Calamity cycle of alluviation.

The effect of the present cycle of trenching has been to remove the greater part of the Kokernot. Channels have been re-excavated in positions almost identical with the channels developed in the interval between deposition of the Calamity and Kokernot formations. That the present drainageways should have followed the pattern of former trenches is not surprising, as erosion of this formation is obviously easier than similar erosion in the more compact Neville and Calamity beds.

ROCK HOUSE GAP AREA

LOCATION

Rock House Gap is located near the western margin of the Marathon Basin about 6 miles east of the northern end of Elephant Mountain (Pl.

FIGURE 1. NEVILLE-CALAMITY CONTACT
Showing veins of illuvial clay some of which cut through gravel lentil at base of the Calamity.

FIGURE 2. ROUNDED INLIER OF NEVILLE OVERLAIN BY CALAMITY FORMATION
Gray sand at top of bank is Kokernot.

FIGURE 3. CALAMITY FORMATION ALONG MARAVILLAS CREEK ABOVE ROCK HOUSE GAP

CLASTIC VEINS; NEVILLE, CALAMITY, AND KOKERNOT FORMATIONS

FIGURE 1. CLAY BOULDER IN BASAL CONGLOMERATIC BEDS OF CALAMITY FORMATION

FIGURE 2. DEPOSITIONAL SYNCLINE IN CALAMITY FORMATION

FIGURE 3. BANDED ALLUVIUM OF CALAMITY DISCONFORMABLY OVERLAIN BY MASSIVE ALLUVIUM OF KOKERNOT FORMATION

CALAMITY FORMATION, ROCK HOUSE GAP AREA

1, loc. 10). Here Maravillas and Dugout creeks join to follow a constricted gap through a ridge of resistant Paleozoic rock. Above the gap the structure of an alluvial flat lying about 15 feet above stream bed is revealed in section along creek banks (Pl. 5, fig. 3). Thinner sections of alluvium occur farther upstream along both creeks.

NEVILLE FORMATION

No intact deposits of alluvium referable to the Neville were found in this area. However, basal conglomeratic beds of the Calamity formation contain blocks of light-brown sandy and silty clay up to 3 feet across (Pl. 7, fig. 1). The clay, which does not closely resemble other alluvium exposed in this area, may have been derived from an underlying deposit of the Neville. Lithologically, the embedded clay blocks resemble alluvium along the banks of Pena Colorado Creek south of old Fort Pena Colorado, 10 miles northeast of Rock House Gap. J. C. Kelley has taken a large elephant tusk from these silty clays, which would seem, therefore, to belong to the Neville.

CALAMITY FORMATION

Exposures.—Alluvium here referred to the Calamity is best exposed along the west bank of Maravillas Creek directly above the gap. Thinner sections occur farther upstream but these were only superficially examined in the vicinity of locality 9.

Lithology.—At locality 10 the lower few feet of the Calamity is generally conglomeratic, as indicated in stratigraphical section 8. The lowest conglomerate beds contain boulders up to 3 feet across but these grade upward into pebbly and sandy beds (Pl. 5, fig. 3; Pl. 6, fig. 3). Caliche is the cementing material.

The coarse clastic beds near the base merge upward into thin-bedded and laminated silty clay, fine sand, and marl (Pl. 6, fig. 3; Pl. 7, fig. 3). Darker laminae consist of gummy carbonaceous clay peppered with small caliche nodules. Lighter beds are of fine quartz sand or marl. Alternation of lighter and darker beds gives the alluvium a banded appearance, which, viewed from a distance, recalls that of varved deposits. Closer inspection shows that with few exceptions individual beds are variable in thickness, discontinuous, and vaguely defined. Color differences are due chiefly to variations in the carbonaceous content.

About 150 yards up Maravillas above its intersection with Dugout Creek, the dark banded silts interfinger with buff calcareous silt and gravel in which carbonaceous materials are restricted to a thin humic zone near the top. Likewise the banded silts disappear upstream along Dugout Creek, giving way to brownish pebbly and gravelly silt like that

seen along the east bank at locality 9. Thus the dark carbonaceous phase of the Calamity formation is restricted to an area a few hundred yards upstream from Rock House Gap.

Thickness.—Maximum exposed thickness above the gap is 14 feet. That the alluvium in this area is relatively thin is indicated by the fact that at Roberts' Ranch, near locality 9, wells strike bedrock at a depth of about 14 feet.

Depositional synclines.—On the south bank of Maravillas Creek near the junction with Dugout Creek, banded alluvium shows shallow synclinal structures up to 50 feet across. Beds between the synclines are nearly horizontal.

Lowest beds in the structures have highest dips. Dips up to 36 degrees were observed in beds along the base of the arroyo-bank (Pl. 7, fig. 2). Five feet above the base, maximum dip in the same structure is 11 degrees. Ten feet above the base, beds are inclined toward the trough of the syncline at angles up to 5 degrees. Strata still higher in the formation maintain a near-horizontal attitude above the synclines. Where sandy beds can be traced through the structures, they are found to thicken appreciably in the troughs, to which, in fact, some layers of lenticular cross section are restricted.

The dips are initial, and the structures they define have resulted from blanket deposition of fine-grained sediments over an uneven terrain. The axes of the synclines mark positions of sloughs which existed from the beginning of the Calamity cycle of sedimentation and which were obliterated only when the valley flat had been built 14 feet above the level of the present Maravillas channel.

Organic content.—Partially decomposed and humified plant material is mainly responsible for the dark color of laminated deposits near the gap. These deposits contain abundant shells of small gastropods. Aquatic species recognized by Professor Cheatum include *Helisoma sp., Gyraulus carus* Pilsbry and Ferriss, and immature shells questionably referred to *Galba cubensis* Pfeiffer. Land shells are represented by a species of *Succinea* and *Hawaiia minuscula* (Binney).

Buried hearths.—The archeological investigation which prompted this study began when Mr. Travis Roberts, local ranchman, discovered hearthstones in wash along Dugout Creek near locality 9. Upon examining the section at this locality, J. C. Kelley was able to prove that the hearthstones are derived from hearths used on a depositional surface buried by continued deposition of the Calamity formation. The hearths are associated with wood-charcoal, and all features of their occurrence recall

those buried in the Calamity formation of the Elephant Mountain area. No hearthstone was found in banded humic deposits near the gap.

Conditions of origin.—The Calamity near Rock House Gap was deposited under conditions similar to those already described for the Elephant Mountain area. In the area just upstream from the gap, the downstream migration of subsurface water was impeded by the relatively impervious bedrock in the gap. Here groundwater was shallow, and marshy conditions prevailed. As a result of deposition under moist conditions the sediments have a relatively high carbonaceous content.

In an effort to understand conditions under which laminated deposits above the gap originated, the writers visited marshy tributaries of Limpia Creek north of Fort Davis. In dry weather some of these streams are chains of stagnant plant-choked pools (Pl. 8, fig. 1). During floods vegetation along channels is swept away while that on the floodplains may be covered with a layer of silt or sand. Little time is required for plants to grow back over the floodplains and again constrict the channelways. A shallow excavation was made by the side of the stream figured on Plate 8. Clean sand and pebble gravel at the surface gave way at a depth between 2 and 6 inches to a layer of fetid black peaty silt. Below this was another layer of clean sand. Evidently the sand records times of high water, the carbonaceous layer an intervening low-water stage of the same year or of years not much separated in time.

Banded deposits above the gap probably had a similar origin. Discontinuous lentils of clean sand record rises of Maravillas and Dugout creeks, while the darker humic layers mark times when the flats were marshy but probably not awash. Thus the layering cannot at present be interpreted in terms of years, and the banding does not have the chronological significance of glacial varves.

KOKERNOT FORMATION

Between the junction of Maravillas and Dugout creeks and Rock House Gap the Calamity formation is intersected by a channel approximately 175 feet wide that is filled by the Kokernot formation (Fig. 7). Within the channel the formation is composed predominantly of gray and brownish silty clay with interbedded gravel. Caliche forms small nodules in the clay, though these are not so large nor so abundant as those in underlying Calamity beds. Upper layers above the channel deposit are continuous laterally with silt forming a thin layer over the alluvial flat.

As in the Calamity-Sheep Creek Valley, hearths and artifacts occur in the upper layers. Where dissection is in progress, gullies are strewn with hearthstone and flint chips.

Both Calamity and Kokernot formations in this area contain considerably more caliche than is characteristic of the beds at the type localities. This reflects the fact that Maravillas and Dugout creeks drain areas underlain to a large extent by limestone, whereas Calamity Creek

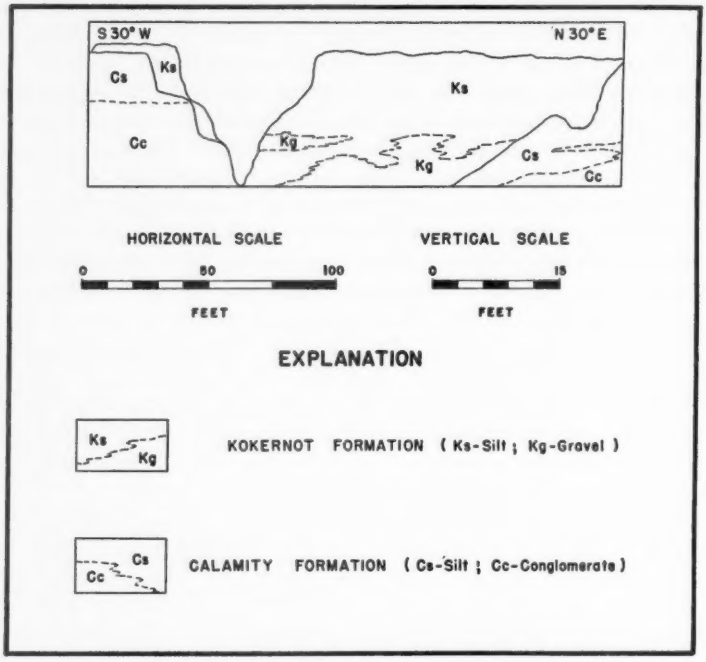

FIGURE 7.—*Section along west bank of Maravillas Creek*

flows across volcanic rocks that supply carbonates less readily and in smaller quantities. The relative quantity of secondary calcium carbonate can be used as a criterion for correlating alluvial formations only when regions of similar climate and bedrock are compared.

RED BLUFF AREA

LOCATION AND GENERAL FEATURES

Red Bluff is the name given to a cliffy escarpment along a butte of volcanic rock lying about 3 miles southwest of Nine Point Mesa (Pl. 1, loc. 11). An unterraced alluvial flat between the mesa and the bluff drains eastward through Nine Point Draw. Investigations were limited

to natural exposures along the draw where it passes the northern end of Red Bluff.

Here, as in the Elephant Mountain area, the alluvial flat is built of three formations whose interrelations are shown diagrammatically in Figure 8.

NEVILLE FORMATION

The Neville consists of buff clayey silt and sand with interbedded gravel. The proportion of coarse material increases toward the bluff, at whose base boulders up to 12 feet across are embedded in the formation (Pl. 8, fig. 2). Root canals lined with caliche ramify the finer sediments, which also contain small gastropod shells (*Succinea luteola* Gould and *S. grosvernori* Lea).

CALAMITY (?) FORMATION

The presence of Calamity alluvium at Red Bluff was not suspected until archeological excavations revealed gravels filling shallow channels in the Neville. Since these fills underlie a midden which is intersected by the Kokernot, the gravel may belong to the Calamity.

KOKERNOT FORMATION

At locality 11 there is exposed in the south bank of Nine Point Draw a channel-filling correlated with the Kokernot (Fig. 8). The filling is approximately 25 feet across and 8 feet thick along the axis of the old channel.

The fill consists mostly of incoherent silt and fine sand with basal and marginal gravel lentils. Intermingled with gravel at bottom and sides of the old channel are artifacts, wood-charcoal, and ash (Fig. 8). This material can be traced up the contact at the base of the channel-fill to its source in an eroded midden exposed at the level of the alluvial flat between the lip of the arroyo and the talus of Red Bluff. Since the midden is intersected by the Kokernot, it must have been abandoned before the cycle of channeling preceding deposition of that formation.

Artifacts in the midden cannot be dated precisely. From archeological evidence he is to present in his report on the area, J. C. Kelley suggests that the culture responsible for the midden could have been in existence as far back as the tenth century A.D. or as late as the thirteenth or fourteenth centuries. On the basis of this suggestion, the cycle of channeling directly preceding deposition of the Kokernot in this area is later than 900-1300 A.D.

ALAMITO AREA

LOCATION AND GENERAL FEATURES

Alamito Creek is the most westerly of the major streams that flow southward from the Davis Mountains (Pl. 1). Near Marfa, headwater

tributaries join to form the main stream, which makes a broad bend toward the east before entering the Rio Grande about 30 miles southward.

Unlike most streams of the area, the Alamito flows the greater part of the year, providing water for a number of small irrigation projects. Per-

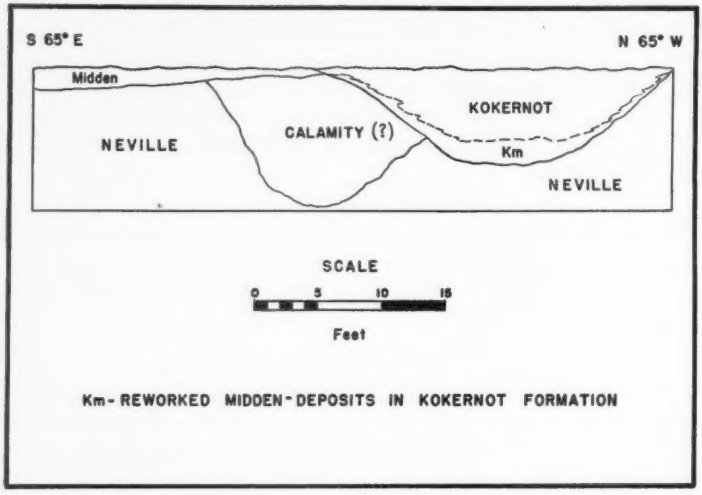

FIGURE 8.—*Section along Nine Point Draw at base of Red Bluff*

ennial water has made Alamito a natural line of communication and settlement between the plains around Marfa and the Rio Grande Valley. The same geographic factors favoring occupation today evidently operated in the past among more primitive cultures, whose relics are embedded in alluvium along the valley.

Along most of its course Alamito is channeled into an alluvial flat which in places lies as much as 25 feet above the bed of the Creek (Pl. 8, fig. 3). Where the channel is constricted between bedrock spurs, the flat has been removed by erosion. Between spurs the flat forms lowland wedges, generally halved by tributaries of Alamito. Thus the longitudinal structure of the flat is revealed along banks of the main stream, whereas transverse structure can be seen along tributaries. Where undissected, the level of the flat is interrupted only where the wind has drifted sand about scattered bushes. Its surface rises almost imperceptibly away from Alamito Creek to points where the alluvium intersects steeper bedrock slopes.

Studies along Alamito Creek were concentrated within two areas: one along Perdiz Creek, a tributary entering the main stream between Marfa

and Casa Piedra, the other along Alamito above the gap which marks its entrance to the valley of the Rio Grande (Pl. 1, loc. 12, 13).

NEVILLE FORMATION

The Neville is exposed for several hundred yards along Perdiz Creek east of the Marfa-Casa Piedra highway (Loc. 13). Tertiary bedrock in this area is stratified white tuff intersected by channel conglomerate and clastic dikes. Overlying the Tertiary unconformably, the Neville consists of putty-colored sand and silt and of conglomerate cemented with caliche. Sand and silt contain abundant caliche concretions up to half an inch across.

No fossils were taken from this alluvium, which is correlated with the Neville because of its high caliche content and its position between bedrock and hearth-bearing beds of the Calamity.

Maximum exposed thickness of the Neville is 5 feet. Relationships of the formation to underlying Tertiary rocks and overlying alluvium are shown in Figure 9, which represents the section observed along the north bank of Perdiz a few yards below the highway crossing.

CALAMITY FORMATION

At locality 13 the Calamity consists of brownish and gray silt and sand with interbedded gravel. Capping the section is a foot of humic silty clay; a second, somewhat thicker, dark zone occurs about a third of the way toward the bottom (Fig. 9; stratigraphical section 9). The beds are less coherent than those of the Neville, and caliche is restricted to whitish films along root canals and worm borings. Here the Calamity rests disconformably on the Neville, and, as in the Calamity-Sheep Creek Valley, the basal contact rises away from the master stream.

A 20-foot section of Calamity is exposed along the east bank of Alamito at locality 12. The basal contact is not apparent, although it may well be only a few inches below pebble and cobble conglomerate cropping out along the base of the arroyo bank. The conglomerate grades upward into calcareous fine gray sand and ashy-gray sandy silt, in turn capped by a thin humic zone about a fourth of the way up the section. Boundaries of the humic zone are not distinct, and thinner dark lamellae above and below give the lower part of the bank a banded appearance. The upper 15 feet tends to be more massive, consisting predominantly of gray sandy silt and sand, locally parted by thin humic zones. At the top of the section is a conspicuous humic layer a foot thick. (See stratigraphical section 10.)

Gastropods from the top of the lower dark zone at locality 12 were identified by Professor Cheatum as *Succinea luteola* Gould and *Hawaiia*

minuscula (Binney). The latter species was found elsewhere only in the laminated silt of the Calamity at Rock House Gap.

Bits of charcoal are scattered through the section although they seem to be concentrated in the humic zones. V. J. Shiner, of Presidio, Texas,

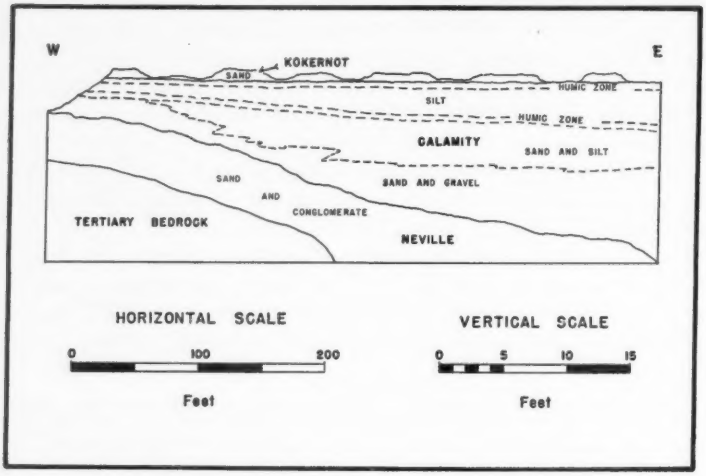

FIGURE 9.—*Section along Perdiz Creek at locality 13*

discovered numerous hearths at the levels of these zones a few hundred yards south of this locality.

KOKERNOT FORMATION

At locality 12 the Calamity is intersected by a channel-filling of the Kokernot (Fig. 10; Pl. 9, fig. 1). Within the old channel the formation consists of incoherent gravel, grit, and sand, which are better sorted than adjacent beds of the Calamity. Fine sand at the top extends outward from the channel and blankets the alluvial flat. Maximum observed thickness of the formation within the channel is 22 feet; over the flat it averages about 2.5 feet. In places the Kokernot has been eroded from the surface of the flat; elsewhere the wind has worked superficial layers into low dunes.

Embedded in upper sandy layers of the formation are the foundations of primitive houses, and associated with the house sites is pottery of several types, including El Paso polychrome. Strata enclosing the pottery and house foundations show by their continuous and horizontal bedding that they have not been reworked by wind since their deposition.

According to J. C. Kelley (Personal communication, June 4, 1939), El Paso polychrome is dated as 1100-1400 A.D. This would indicate that Kokernot deposition was nearing an end in this area within the interval between the twelfth and fifteenth centuries.

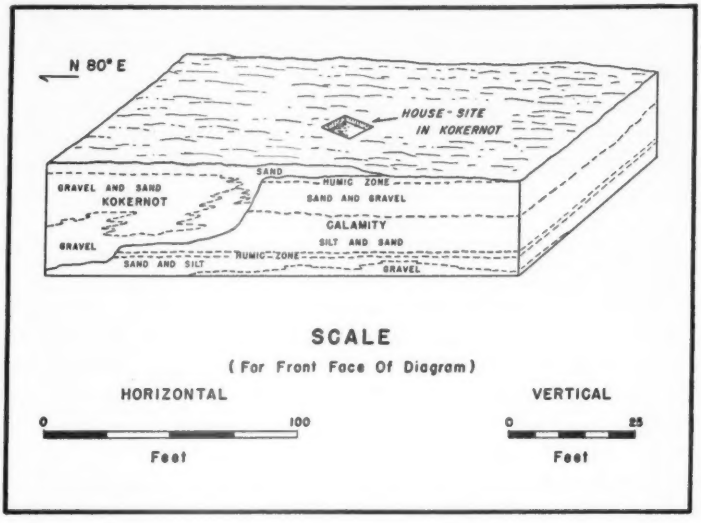

FIGURE 10.—*Diagram showing structure of alluvial flat along east bank of Alamito Creek*

VALENTINE-FORT DAVIS AREA

GENERAL FEATURES

At Marfa the longitudinal lowland which is largely drained by Alamito Creek divides into two branches. One branch extends to Fort Davis, where it drains to the northeast through headwaters of Limpia Creek. The other branch, followed by the Southern Pacific Railway, extends northwest to Valentine and beyond. A low divide near Ryan, between Valentine and Marfa, separates the Alamito drainage from that leading interiorly into Salt Basin. Between the two lowland branches a lobe of the Davis Mountains projects toward the south (Pl. 1). For purposes of reference the triangular area with Valentine, Fort Davis, and Ryan at the apices will be called the Valentine-Fort Davis area.

In this area there are such abrupt transitions between mountains on the north and plains to the south that the mountains seem much higher

than they are. Actually, the relief is about 2000 feet. The plains incline away from the mountains toward Alamito and other major streams, and slopes as much as 800 feet to the mile along the mountain front give way within short distances to gentler inclinations averaging 50 feet per mile. At the border of the mountains the surface of the plains rises to intersect steep or cliffy slopes, so that the boundary between mountains and plains is sharply defined. This boundary is sinuous; many park-like embayments indent the mountain front, and many outlying hills are scattered over the plains.

At several places adjacent to the Davis Mountains the plains are carved from the same igneous bedrock that forms nearby mountains and hills. Generally, however, the bedrock floor is concealed by a cover of alluvium, sections of which are found along discontinuous arroyos radiating from the mountain lobes. Some arroyos have low walls of alluvium and floors of bedrock; others have trenched through as much as 15 feet of alluvium without reaching bedrock. As Tertiary rocks crop out along the banks of Alamito and Limpia creeks, to which the surface of the plains is graded, the alluvial cover between these streams and the mountains probably does not exceed a few tens of feet in thickness. Thus the alluvium forms a thin mantle above a bedrock pediment, which must be more remarkable for the prevailing evenness of its slope than for any minor irregularities such as become apparent in an investigation of the materials that cover its surface.

The alluvium was studied at two localities, numbered 14 and 15 of Plate 1. In both places there are equivalents of the Neville, Calamity, and Kokernot formations.

NEVILLE FORMATION

The Neville crops out as rounded inliers along the lower banks of a small arroyo trending southwest through locality 14. The formation consists of reddish-brown silty clay in which large caliche nodules are abundant (Pl. 9, fig. 2). In places the nodules have grown together so as to form massive layers as much as 2 feet thick. Interbedded with the silty clay are lentils of conglomerate, likewise cemented with caliche. Scattered through the clay are horse teeth and small bone fragments. The base of the Neville cannot be seen in this area; maximum exposed thickness is 6 feet.

At Skillman Grove (loc. 15) a section of the Neville 10 feet thick is exposed in the headwall of an arroyo which skirts the northern edge of a hill. Exposures at this locality are similar to those already described, except that there is less caliche in the Neville at Skillman Grove.

FIGURE 1. MARSHY TRIBUTARY OF LIMPIA CREEK
North of Fort Davis

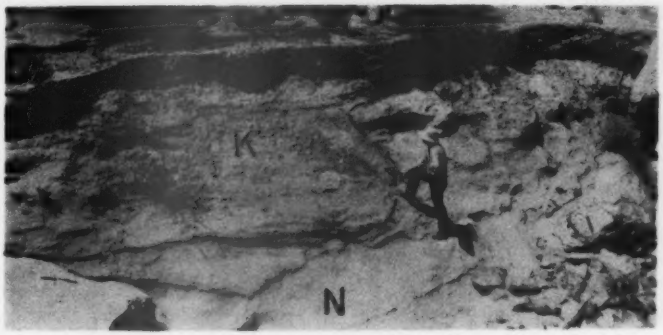

FIGURE 2. SOUTH BANK OF NINE POINT DRAW AT LOCALITY 11
Showing channel-filling of Kokernot (K) in bouldery beds of the Neville (N).

FIGURE 3. DISSECTED ALLUVIAL FLAT ALONG ALAMITO CREEK
Viewed upstream near locality 12.

MARSHY CREEK; ALLUVIUM AT RED BLUFF AND ALONG ALAMITO CREEK

FIGURE 1. CHANNEL-FILLING OF KOKERNOT (K) IN CALAMITY (C)
East bank of Alamito Creek, locality 12.

FIGURE 2. CALICHE NODULES IN SILTY CLAY OF NEVILLE FORMATION
Locality 14.

FIGURE 3. HEARTHSTONE (BETWEEN HAMMERS) IN PEBBLY GRIT OF CALAMITY FORMATION
Locality 15.

CALAMITY FORMATION

At locality 14 the Calamity formation attains a maximum exposed thickness of 15 feet. The formation consists of brownish gritty silt with interbedded gravel. Although caliche forms thin films in root canals and not uncommonly makes a whitish coating over pebbles in the gravel, it does not occur in concentrations comparable with those in the underlying Neville.

J. C. Kelley has discovered several hearths weathering from the Calamity near the head of the large tributary shown in the northern part of the map on Figure 11. Here, as in areas previously described, the Calamity rests disconformably on the Neville.

At locality 15 the Calamity attains a maximum thickness of 13 feet, forming the south bank of the arroyo headwall a few yards east of the Skillman camp ground. The lower half of the formation is of reddish and gray silt with basal gravelly layers channeled into the Neville. The upper half consists of two layers of silt separated by a bed of brownish gritty silt, each of the three units averaging 2 feet in thickness. Hearths, flint chips, and bits of charcoal occur at several horizons, especially in a carbonaceous grit 5 feet above the base of the section (Pl. 9, fig. 3; stratigraphical section 11).

KOKERNOT FORMATION

Along the arroyo at locality 14 the Kokernot fills channelways as much as 15 feet deep excavated in the Calamity and Neville formations. Within the channels the formation consists basally of incoherent rusty pebble and cobble gravel with scattered boulders. In most places the gravel grades upward into alternating thin beds of dark silty grit and black humic clayey silt with subcubical fracture. Near the top the beds become less humic, passing into gray sand, which extends out laterally from the channelways to form a thin covering over the alluvial flat. In this area channels filled with the Kokernot intersect the present arroyo banks at places sufficiently numerous to permit reconstruction of part of the drainageway that developed before deposition of the Kokernot. Figure 11 shows the pattern of the old channel. A typical section of the old channelway with its filling of dark Kokernot alluvium is shown in Figure 1 of Plate 10.

Figure 11 shows that the present arroyo has tended to follow the outcrop of the incoherent Kokernot channel-fill, which provided a natural line of least resistance across the flat. With continued lateral cutting, the present stream will destroy the channel phase of the Kokernot, leaving only thin floodplain deposits as evidence of the last cycle of alluviation.

Similar channel-fillings occupy depressions up to 6 feet deep in the

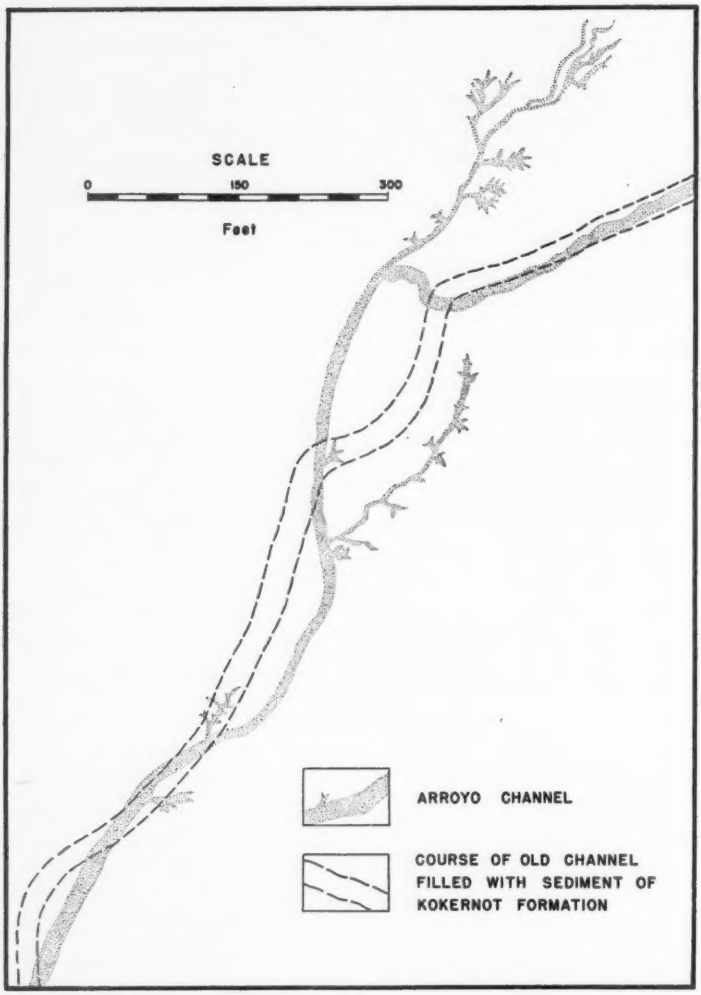

FIGURE 11.—*Map showing pattern of Kokernot channel fill*

Calamity and Neville alluvium along the arroyo at locality 15. Along most of the arroyo, however, the Kokernot is represented only by thin sandy layers at the top of the banks. The sand rests with undulatory contact on older alluvium.

ALPINE AREA

GENERAL FEATURES

Alpine is situated on a lowland hemmed in on the north, west, and south by the Davis Mountains, and bordered on the east by a broken line of hills continuing along the strike of the Del Norte range (Pl. 1). The surface of the lowland is that of a smoothly contoured concave plain slanting northeast and draining toward the Pecos River through Lencito Draw. Tributaries of Lencito radiate back into the Davis Mountains, and the flats which border these streams expand near their headwaters into spacious intramontane meadows.

Over most of the lowland, within the mountains and in the plains around Alpine alike, bedrock is covered with alluvium. Apparently the alluvial cover is only a few feet thick, for many shallow arroyos have cut down to bedrock along parts of their courses.

NEVILLE FORMATION

The Neville crops out in banks up to 15 feet high along the tributary of Lencito Draw that parallels the Southern Pacific Railway (Pl. 1). The lowest exposed beds consist of gravel that is in many places tightly cemented with caliche so as to form conglomerate (Pl. 10, fig. 2). Gravel grades upward into pebbly buff sandy silt, and, where the formation is not intersected by younger alluvium, a dark humic zone as much as 3 feet thick is preserved at the top. White caliche pellets occur in the humic silty clay.

Teeth and bones of mammoth and horse are scattered through the pebbly silt. J. C. Kelley has discovered mammoth bones at locality 17, and locality 18 has long been a favorite of local collectors of elephant teeth and tusks. Among the fossils taken from this locality Professor A. S. Romer has identified the teeth of *Archidiskodon imperator*.

CALAMITY FORMATION

No alluvium that can be correlated with the Calamity was seen along mountain tributaries of Lencito Creek. It would seem that at a time when, after deposition of the Neville, most alluvial flats in the Davis Mountains were being dissected, headwardly eroding streams did not find their way into some of the higher intramontane flats situated near major divides. After the Neville cycle of alluviation the flat around locality 18 appears not to have been channeled until the erosional epoch directly preceding deposition of the Kokernot.

KOKERNOT FORMATION

Along the tributary paralleling the railway the Kokernot consists of unconsolidated silt, sand, and gravel. Gravel and interbedded sand fill

narrow channel-depressions up to 14 feet deep. A layer of silt averaging a foot thick extends outward from above the channels over the surrounding flats. At locality 18 a channel-filling of the Kokernot is being excavated by a small tributary arroyo (Pl. 10, fig. 3). This filling occupies a channel which was itself tributary to an arroyo whose course has been followed by the present stream. Here, as in the Valentine-Fort Davis area, streams have established their courses along fillings of incoherent Kokernot alluvium.

DEPOSITS IN CAVES AND SHELTERS

The mountains south and west of Alpine are carved from nearly horizontal layers of lava and volcanic breccia interstratified with fine-grained tuff. Valleys and gentle upland slopes are generally developed on tuff. The hills are mostly mesas, capped by lava and breccia. On the mountain slopes the more resistant beds crop out as cliffy escarpments, like the risers of a set of stairs. In many places the base of these "risers" is marked by a line of shelters and shallow caves. Professor V. J. Smith, of Sul Ross College, has made a specialty of studying and describing the archeology of the caves and shelters, many of which are floored with thick middens. Recently J. C. Kelley has investigated the stratigraphy of several of the larger caves and has established the basis for a likely correlation between the cave deposits and the alluvium of the valley flats.

Several caves and shelters are located around the border of Sunny Glen, a circular dell drained by one of the headwater tributaries of Lencito Draw (Pl. 11, fig. 1). Deposits in Rock Cave, at the eastern margin of the glen (loc. 16), were trenched (Pl. 11, fig. 2). Excavations revealed that the midden deposits forming an almost level floor and extending downward to depths of about 2 feet overlie loose debris consisting of angular rocks admixed with dark dust containing flint chips and hearths. The debris, as thick as 8 feet in places, in turn rests on yellowish and reddish-brown compact dust, which ranges in thickness up to 5 feet.

The yellowish dust rests upon the bedrock basement of the cave. It is so finely divided and so readily suspended in the atmosphere that workers were obliged to wear masks when digging through it. The material consists of angular particles of quartz, feldspar, and mineral grains coated with iron hydroxide, to which the yellow and reddish hues of the deposit are due. Individual particles range in size from that of fine silt to that of clay. This material encloses rock fragments as much as several feet in diameter, all of which seem to have fallen from the roof while the dust was accumulating. Although the fine materials are massive, a crude semblance of stratification is imparted to the entire deposit by the em-

FIGURE 1. SECTION OF OLD CHANNEL IN NEVILLE FORMATION (N) FILLED WITH THE KOKERNOT (K)
Locality 14.

FIGURE 2. CONGLOMERATE WITH CALICHE CEMENT
Neville formation, near locality 17.

FIGURE 3. GULLY DEVELOPED ALONG CHANNEL-FILLING OF KOKERNOT
Locality 18.

FIGURE 1. SUNNY GLEN
Viewed toward west from locality 16.

FIGURE 2. ENTRANCE TO CAVE AT LOCALITY 16.

bedded rock fragments, which generally lie with their longer dimensions paralleling the contours of the floor. No fossils or objects of human workmanship were found in the deposits of yellowish dust.

In Merriweather Cave, 9 miles north of Alpine and a mile west of the Fort Davis-Alpine highway, J. C. Kelley found deposits similar to those already described. Middens forming the floor of the cave overlie barren yellowish dust enclosing fallen rock fragments. This relationship between basal dusty deposits and overlying middens is reputed to be common to many caves in the Davis Mountain area. Kelley was able to show that middens at Merriweather Cave are not all of the same age but have resulted from at least two occupations by different cultures. Older middens, most commonly preserved along the back and side walls of the cave, contain Pecos River points like those found in the Calamity formation. Overlapping the older middens and occupying a more central position within the cave are younger heaps of refuse containing points like those found in the pre-Kokernot midden at Red Bluff (J. C. Kelley, personal communication, April 22, 1939).

Pecos River points are evidence for correlating older Merriweather middens with the Calamity formation. It follows that the barren dust beneath the middens is probably older than the Calamity. The color of the dust, reddish and yellowish-brown, is that of the Neville formation, and the absence of artifacts both within the dust and in the Neville is a negative feature common to both deposits. Either the dust was deposited in the caves while the Neville was being deposited on the flats, or the dust was derived from the Neville while that formation was being dissected. A third possibility is that the lower portion of the dusty deposits was laid in caves during deposition of the Neville, whereas the upper portion was deposited while the Neville was being dissected. The questions thus raised involve the origin of both the cave dust and of the Neville formation.

That the fine-grained cave deposits have not resulted from weathering of rock *in situ* is indicated by the sharp contact between unweathered rock and overlying dust, which can be swept cleanly away from the hard bedrock floor. The dust has been brought into the caves from without, and no transporting agent other than the wind could have taken materials so uniformly fine and stored them away in recesses at different elevations along the mountainsides.

It is unlikely that the windblown dust was transported to the caves from any great distance; with prolonged transport individual particles would have lost by attrition the thin coatings of iron hydroxide that color most of them. The source of the deposits was probably in adjoining valley flats, which contain reddish fine-grained silt and clay of the Neville.

Prevalence of root canals through the Neville silt and clay as well as the occurrence of fresh-water gastropods and mammoth remains in these deposits seem to indicate that the valley flats were covered by grass and brush during the Neville cycle of alluviation and hence were protected from deflation. On the other hand, when the Neville was first dissected, fine clay and silt were bared along the sides of flaring arroyos, and the wind must have been free to pick up this material in quantities and whisk it into caves and shelters.

The writers believe that the yellowish dust underlying the older middens in caves was derived from the Neville during the cycle of channeling directly preceding deposition of the Calamity.

STRATIGRAPHICAL SECTIONS

Eleven sections are listed herewith. Color names are from Maerz and Paul (1930).

Section 1 (Measured at locality 3)
(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
6. Clayey and sandy silt interbedded with silty sand; slightly calcareous; color adobe	0.5–13
Disconformity	
Calamity formation	
5. Calcareous clayey silt and sand with interbedded gravel; silt and sand break into irregular crumbs which show sections of minute tubular perforations lined with white films of caliche; color, winter leaf	0–12.5
Disconformity	
Neville formation	
4. Pebbly, sandy, and clayey silt with irregular caliche nodules up to 1 inch in diameter; color, suntan	2–7
3. Silt with embedded pebbles and cobbles; strongly impregnated with caliche, which forms thick white crusts in places	0–2
2. Calcareous, sandy, clayey silt and pebbly sand containing fragments of elephant tusks and small gastropod shells; color, lariat	0–3
1. Cobble and boulder conglomerate with matrix of sand cemented with caliche	0–4
Total exposed thickness	13
Unconformity	
Tertiary bedrock	

Section 2 (Measured at locality 2)
(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
4. Gray silt and fine sand with lentils of pebble and cobble gravel	4–6
Disconformity	
Calamity formation	
3. Compact, calcareous, humic silt with embedded pebbles; perforated by worm borings and root canals; color, Deauville sand	1

	Thickness in feet
Quaternary *(continued)*	
Calamity formation (continued)	
2. Calcareous sandy and clayey silt perforated by worm borings and root canals; color, oak buff	2
1. Calcareous silty and clayey sand with interbedded gravel; fine-grained beds perforated by worm borings and root canals; charcoal and hearthstone fairly common in this unit; color, tansan; base not exposed	7–8+
Total exposed thickness	15

Section 3 (Measured at locality 5)
(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
5. Gray quartz sand	0.5
Disconformity	
Calamity formation	
4. Clayey silt showing discontinuous lamination; upper 4 feet humic; color, adobe	6.5–9
3. Fine sand with admixed silt and clay; color, thrush	0.5
2. Clayey silt with interbedded sand; vaguely laminated toward base; upper 2 feet humic, with subcubical fracture; average color, blondine	3.5–6
Disconformity	
Neville formation	
1. Calcareous, silty clay perforated by minute vermicular tubules lined or filled with caliche; local interbeds of sand and gravel; color, aloma; base not exposed	4.5+
Total exposed thickness	16.5

Section 4 (Measured at locality 6)
(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
7. Fine sand and silt of angular quartz; color, blondine	1
Disconformity	
Calamity formation	
6. Compact, silty, humic and calcareous clay with scattered rock granules; breaks into irregular crumbs showing sections of root canals; grades into unit 5 without pronounced break; color, winter leaf	1–1.5
5. Silty and pebbly sand with interbedded pebble gravel; color, adobe	4.5–5
Disconformity	
4. Silt and sand with scattered pebbles	0.5–1.5
3. Clayey silt and sand with scattered pebbles; upper 2 feet humic, like unit 6; color, adobe to santos	4–4.5
2. Pebble and cobble gravel	0.5–1
Disconformity	
1. Ferruginous clay and silt perforated by minute tubular openings lined with white caliche films; color, suntan; base not exposed	0.5+
Total exposed thickness	13

Section 5 (Measured along north bank of Sheep Creek 75 feet above intersection with Calamity Creek)

(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
4. Silt and sand with interbedded pebble gravel	1–2
..... Disconformity	
Calamity formation	
3. Silty humic clay with rude columnar jointing; perforated by worm borings and root canals; grades into unit 2 without pronounced break; color, beaver	4–5
2. Laminated clayey silt and fine sand with lentils of grit and pebble gravel; color, suntan	5–9
..... Disconformity	
Neville formation	
1. Silty clay with abundant caliche nodules up to 1 inch across; perforated by minute tubular openings lined with caliche; color, aloma; base not exposed	5+
Total exposed thickness	15

Section 6 (Measured at locality 7)

(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
5. Gray silt and sand with basal pebble to boulder gravel	0.5–12
..... Disconformity	
Calamity formation	
4. Humic pebbly and clayey silt with hearths near base; grades into unit 4 without pronounced break	1.5–5
3. Sandy and clayey calcareous silt with scattered pebbles and gravel lentils; boulder gravel at base of unit cemented with caliche in places; average color, grain	5–10
..... Disconformity	
Neville formation	
2. Clayey and silty sand; highly calcareous, with abundant caliche nodules averaging approximately half an inch in diameter; numerous small tubular perforations; color, sundown	0–2+
Total exposed thickness	13
Cretaceous	
1. Marl and calcareous shale	2+

Section 7 (Measured at locality 8)

(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
5. Light gray pebbly sand and silt	1
..... Disconformity	
Calamity formation	
4. Brownish sandy silt, with darker humic zones at top and bottom containing hearths	4
3. Calcareous sandy and clayey silt; upper 2 feet humic; average color, suntan	5.5
2. Compact calcareous clayey silt, thin-bedded to massive; bits of charcoal occur in beds 3 feet above base of this unit; color, tansan	9

	Thickness in feet
Quaternary *(continued)*	
Calamity formation (continued)	
1. Interbedded calcareous clayey silt and sand with lentils of pebble, cobble, and boulder gravel	11+
Total exposed thickness	30
..... Unconformity	
Cretaceous (Del Rio formation)	

Section 8 (Measured at locality 10)

(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
3. Gray to brownish clayey silt with interbedded sand and gravel; small calcareous concretions along bedding surfaces; hearthstone abundant in upper layers	0–16
..... Disconformity	
Calamity formation	
2. Alternating thin beds of dark humic clay, and lighter layers of sandy and silty marl grading into calcareous sand; sand and dark clay contain small caliche nodules	0–14
1. Gravel and conglomerate cemented with caliche; conglomerate contains blocks of sandy and silty clay as much as 3 feet across	0–9
Total exposed thickness	16

Section 9 (Measured at locality 13)

(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
7. Incoherent gray sand	0–1.5
..... Disconformity	
Calamity formation	
6. Dark humic silty clay with subcubical fracture	0–1
5. Brownish pebbly fine sand and sandy silt, perforated by root canals lined with thin caliche films	0–2.5
4. Dark humic silty clay with subcubical fracture; forms massive unit grading upward and downward into alternating thin beds of brownish and dark-gray sandy silt	0–2
3. Incoherent gray sand, grit, pebble and cobble gravel in cross-bedded, lenticular units; becomes finer toward top, grading into brownish sandy silt perforated by root canals	0–5
2. Brownish silty sand with basal gravelly layer; thin films of caliche line small tubular perforations	0–5
..... Disconformity	
Neville formation	
1. Brownish fine sand and silt with scattered caliche-coated pebbles and cobbles, and abundant caliche nodules; at top of unit is a conglomerate cemented with caliche	0–5
Total exposed thickness	15
..... Unconformity	
Tertiary tuff and conglomerate	

Section 10 (Measured at locality 12)

(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
6. Gray sand and grit with interbedded gravel	2–22
Disconformity	
Calamity formation	
5. Gray fine sand with interbedded gravel lentils; dark humic zone 1 foot thick at top; bits of charcoal common in basal layers	0–7
Minor disconformity	
4. Compact, massive, ash-gray sandy silt and fine sand grading downward into laminated silt and sand; laminated portions consist of alternating layers of dark carbonaceous silty sand and fine gray sand; charcoal common in lower layers	0–8
3. Carbonaceous silt with subcubical fracture; contains bits of charcoal, probably derived from buried hearths; color, sombrero	0–1.5
2. Alternating layers of carbonaceous silty sand and fine gray sand in beds up to 6 inches thick	0–4
1. Pebble and cobble gravel with matrix of fine sand and grit; cemented with caliche in places; gravel grades upward into fine gray sand containing tubular caliche concretions; base not exposed	0–2.5
Total exposed thickness	23

Section 11 (Measured at locality 15)

(Descending Order)

	Thickness in feet
Quaternary	
Kokernot formation	
8. Unconsolidated gray silt and fine sand	0–1
Disconformity	
Calamity formation	
7. Dark humic gritty silt	2
6. Reddish to buff gritty silt	2
5. Pebbly humic silt and clay with columnar fracture	2.5
4. Pebble and cobble gravel	0.5
3. Carbonaceous grit containing hearths and abundant charcoal	1
2. Reddish-brown to gray silt interbedded with sand and gravel; contains bits of charcoal	5+
Disconformity	
Neville formation	
1. Silty clay with interbedded pebble and cobble gravel; color, blush	0–10
Total exposed thickness	16
Unconformity	
Tertiary bedrock	

HISTORY OF THE VALLEY FLATS

SEQUENCE OF EVENTS

In the Davis Mountains and vicinity, lowlands developed as broad erosional valleys and partial pediments have been filled and channeled alternately during the Quaternary. Most of the valleys contain three bodies of alluvium of different ages. Some intramontane valleys south of Alpine appear to contain only two bodies of alluvium but these can be

identified with two of the three formations with type localities in the Calamity-Sheep Creek Valley. Thus the major episodes in the physical history of the Quaternary consist of a long period of erosion in which the broad valleys were developed, three stages of alluviation, and three episodes of erosion by channeling.

The earliest geological event assignable to the Quaternary is the development of the broad valley system, although this process probably began in the Tertiary. The streams flowed largely over bedrock and formed the broad rock floors characteristic of the region. Then began the deposition of the Neville formation. As the valleys were aggraded, the streams shifted their courses from time to time, spreading the alluvium so as to build broad flats. Grasses and shrubs took root in interstream areas, providing forage for species of elephant and horse now extinct.

When the axial portions of the valleys had been filled to depths averaging about 20 feet, the streams ceased aggrading, and much of the Neville was rather deeply weathered, so that clay seams and caliche were developed. Hereafter the streams began cutting channels into the Neville alluvium. Channeling was widespread, and all except the more isolated highland meadows near divides were dissected. Flaring gullies, some a hundred yards across, were opened. Presumably at this time the wind eroded the bare banks and beds of these gullies and carried quantities of reddish clay and silt up from the valley floors into rock shelters and caves along the slopes of adjacent mountains. The mammoth seems to have disappeared from the Davis Mountains during this dusty time.

Following this stage of dissection the streams once more began to aggrade. Deposition of the alluvium, here called the Calamity formation, took place, and the gullies developed in the Neville were filled. During pauses in this process of sedimentation plants grew in the gully bottoms, and dark humic residues stained the alluvial floors. During such pauses primitive man camped along the streamways, where he built his fires and occasionally buried his dead. Sediment recurrently brought down by floods covered hearths and burials, until finally the gullies were filled to the level of the surrounding alluvial flat. At this level a dark humic zone was generally developed, and cracks in the alluvium were filled with dark-gray silty clay.

The process of filling was interrupted a second time by the incising of streams into both the Calamity and Neville alluvium. Steep-walled gullies or arroyos a few tens of feet across developed rapidly in the incoherent alluvium of the Calamity formation and less rapidly in the more resistant Neville, until in many places bedrock was exposed in the bottoms of the arroyos. Before the flats had become maturely dissected, however, the streams began to deposit, filling the channels or arroyos with the Kokernot

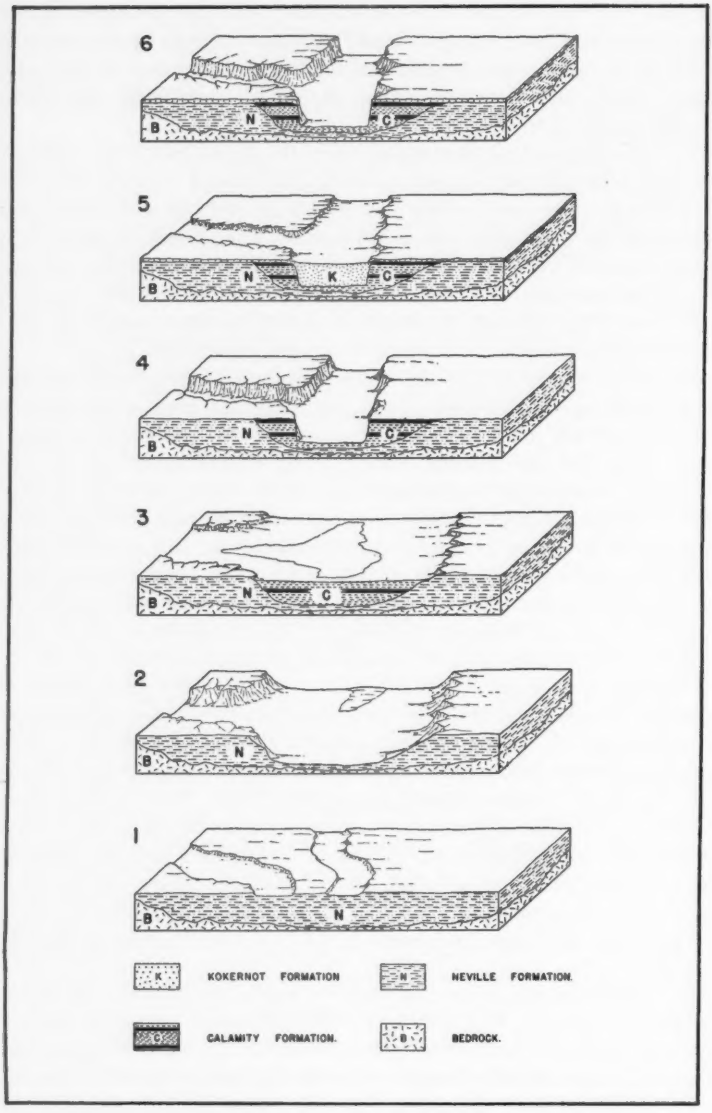

FIGURE 12.—*Diagrams illustrating development of valley flats*

alluvium. Filling continued until the stream beds were brought to the level of the alluvial flats. Floodwaters escaping the channels spread sand and silt over the flats, which were built about a foot above their former grades. In places the sand and silt buried campsites and the foundations of shelters built by the contemporary occupants of the region.

A third cycle of channeling began after deposition of the Kokernot and continues until the present. These gullies are recent; as in other parts of the Southwest, many have been formed, and all have been enlarged, since the settlement of the region (Bryan, 1925). Recent arroyos have followed lines of least resistance offered by channel-depressions filled with incoherent sand and gravel, so that now almost all of the Kokernot, except for thin floodplain phases, has been destroyed by erosion.

This history is summarized in the six diagrams of Figure 12. Diagram 1 shows a valley flat formed of Neville alluvium; diagram 2 depicts the same area after the first cycle of channeling. Diagram 3 shows the area as it may have looked near the end of Calamity sedimentation. Block 4 shows the flat trenched by gullies which developed during the second cycle of channeling, and number 5 shows the gullies filled with Kokernot alluvium. Diagram 6 shows the gullied valley flats as they appear today.

RELATIVE DURATION OF EVENTS

The relative volumes of the Neville, Calamity, and Kokernot formations stand in direct proportion to the relative ages of the formations. In general the Calamity fills channels in the Neville, and the Kokernot fills channels largely cut in the Calamity. Thus regionally there was less alluvium deposited during the Kokernot or most recent cycle of sedimentation than during the preceding Calamity cycle, and less during the Calamity than during the Neville cycle. Though it cannot be assumed, even for a relatively limited area, that rates of erosion and sedimentation have been constant, it would appear that more time was required for deposition of the Neville than for the Calamity, and more for the deposition of the Calamity than for the Kokernot. Moreover, as the Calamity fills channels more spacious than those occupied by the Kokernot, it would seem that the post-Neville, pre-Calamity interval of erosion was of longer duration than the post-Calamity, pre-Kokernot interval. It appears, therefore, that the major intervals of Quaternary sedimentation and erosion have become progressively shorter from the beginning of Neville sedimentation until the present.

As yet this generalization cannot be proved by referring the periods of sedimentation to any standard chronology. The Neville contains the bones of extinct mammoths and horses. Thus a considerable antiquity is implied, but there is no agreement as to what part of Quaternary time is indicated by the presence of these animals. Romer (1935) has discussed

the problem at length and holds that both the mammoth and the horse may be quite recent. Finds of artifacts associated with mammoth are now quite numerous (Wormington, 1939), and artifacts associated with horse bones have been reported by Bird (1938). Thus finding artifacts in the Neville seems probable in spite of the failure to do so during this investigation. On the other hand both the mammoth and the horse were in existence for a relatively long time, and it is possible that the Neville was deposited before man entered the area. The period of deposition may also have been very long, so that the parts of the formation best exposed may be the parts that are relatively ancient, and the parts that may be more recent are concealed. Such a hypothesis is special pleading, but there is a possibility that it explains the lack of artifacts.

Some of the Kokernot floodplain deposits overlapping channel phases of the same formation were laid down between 1100 and 1400 A.D., as proved by embedded El Paso polychrome pottery. Kelley believes that the midden at Red Bluff which is older than the post-Calamity, pre-Kokernot erosion could have been occupied as early as 900 A.D. or as late as 1300. Pecos River points in the Calamity belong to a cultural complex the whole of which was tentatively dated by Setzler as 700 A. D. But even if all these dates were substantiated, they would not suffice to fix beginnings or ends of major physical events in the history of this area. However, these dates and estimates suggest that the Calamity and Kokernot formations are of no great antiquity even as historical time is reckoned and that only a few hundred years were required for channeling of the valley flats and filling of these channels with Kokernot alluvium.

CAUSE OF ALTERNATE ALLUVIATION AND CHANNELING

Conceivably the alternate filling and channeling of the flats could have developed in response to structural or to climatic changes.

Local structural disturbances, such as faulting or warping, did not control sedimentation and erosion in the flats because: (1) Nowhere in the areas examined is the alluvium faulted, even where it overlies faults in bedrock. (2) Older alluvial beds were not tilted or warped before younger beds were deposited. (3) Local structural disturbances could not account for the nice balance that has been maintained between levels to which the flats have been alternately channeled and aggraded (Fig. 12).

On the other hand, changes in the regimen of streams resulting from climatic fluctuations are adequate causes for the alternate erosion and sedimentation of the valleys. Under the relatively mild climate of the Davis Mountain region rainfall is the climatic factor most likely to have determined whether the streams would aggrade or would dissect the valleys. The reddish color of the Neville alluvium, the high percentage of

clay and fine silt in the formation, the presence of abundant root canals, bones of herbivorous animals, and shells of aquatic gastropods suggest that the formation was deposited under relatively humid conditions.

That the cycle of erosion following Neville deposition progressed under more arid conditions is suggested by the occurrence of cave-dust, which likely was derived from the Neville and deposited before deposition of the Calamity. Moreover, during this interval of stream channeling mammoths seem to have disappeared from this region, as their remains are not found in the Calamity and Kokernot formations. Increasing dryness with consequent decrease in vegetation would have been sufficient cause for migration or local extinction of these large herbivores. Furthermore, the relative abundance of mammoth bones in high intramontane valleys suggests that during closing stages of Neville sedimentation increasing dryness had driven these animals from the lowlands peripheral to the Davis Mountains to relatively more moist highland pastures.

If the Neville sedimentation occurred during a relatively humid time, and if the following cycle of gullying proceeded under relatively arid conditions, it is fair to suppose that these and subsequent cycles of erosion and sedimentation have been governed by long-period fluctuations in rainfall.

CORRELATION OF FORMATIONS

At present the numerous bodies of alluvium assigned to the Quaternary of the southwestern United States have not been described in sufficient detail to permit final or even a sure correlation of the Neville, Calamity, and Kokernot formations with alluvial beds in neighboring areas. However, preliminary accounts of alluvial deposits in the Abilene area of Texas and in the Black Mesa and Rainbow Plateau region of northern Arizona warrant the tentative comparisons shown in Table 1.

The nearest Quaternary sequence for which both archeological and geological data are available is that around Abilene, Texas, about 200 miles northeast of Alpine. Leighton (1936) has subdivided alluvium in valley flats of this area into three formations: Durst silt, Elm Creek silt, and unnamed floodplain deposits, in order from oldest to youngest (Fig. 13).

The Elm Creek, according to Leighton, consists of silt and sandy silt with minor quantities of sand and gravel. Dark humic zones like those in the Calamity occur in the formation and contain hearths and artifacts. J. C. Kelley (personal communication, April 22, 1939) states that there are typological affinities between certain artifacts from the Elm Creek and the Pecos River points characteristic of the Calamity. It is on this evidence that the Calamity and Elm Creek formations are tentatively correlated.

Near Albany, Texas, about 30 miles northeast of Abilene, Kelley found surficial gray sand disconformably overlying reddish silt with humic zones. The underlying silt is probably Elm Creek, and the sand is equivalent to the floodplain deposits represented by number 3 in Leighton's diagram

TABLE 1.—*Tentative correlation of the Neville, Calamity, and Kokernot formations*

	Davis Mountain Area	Abilene area (Leighton, 1936)	Northern Arizona (Hack, 1939)	Climate postulated
QUATERNARY	Kokernot	Unnamed floodplain deposits (Fig. 13, number 3)	Number 3 fill	More humid
	Disconformity	*Disconformity*	*Disconformity*	Less humid
	Calamity	Elm Creek silt	Number 2 fill	More humid
	Disconformity	*Disconformity*	*Disconformity*	Less humid
	Neville	Durst silt	Number 1 fill	More humid
	Unconformity	*Unconformity*	*Unconformity*	?
Pre-Quaternary bedrock				

(Fig. 13). From the sand were taken artifacts which Kelley found to be nearly identical with those forming a cultural horizon in the Kokernot formation. Thus the unnamed floodplain deposits resting upon the Elm Creek silt in the Abilene area can be tentatively correlated with the Kokernot.

Disconformably underlying the Elm Creek silt and unconformably overlying bedrock in the Abilene area is the gravel and pebbly silt of the Durst, distinguished from younger alluvium by its darker red color, more compact texture, evidence of deep weathering, and higher content of caliche. It is likely that the calcareous alluvium from which Ray and Bryan (1938) took a Folsomoid point and mammoth bones belongs to this formation. The occurrence of mammoth bones in the Durst would in itself not be conclusive evidence for correlating the formation with the Neville, as in the Abilene area the Elm Creek silt likewise contains mammoth remains (Leighton, 1936, p. 35). There is no paleontological and archeological evidence for correlating the Neville and Durst, and the comparison between the two formations in Table 1 is based on their similar positions with respect to bedrock and to overlying alluvium containing artifacts with typological affinities.

Hack (1939) has shown that several valleys of northern Arizona have undergone alternate channeling and filling at least three times during the later part of the Quaternary. In Jeddito Valley three sets of alluvial fill form as many terraces along the present wash. The oldest alluvium,

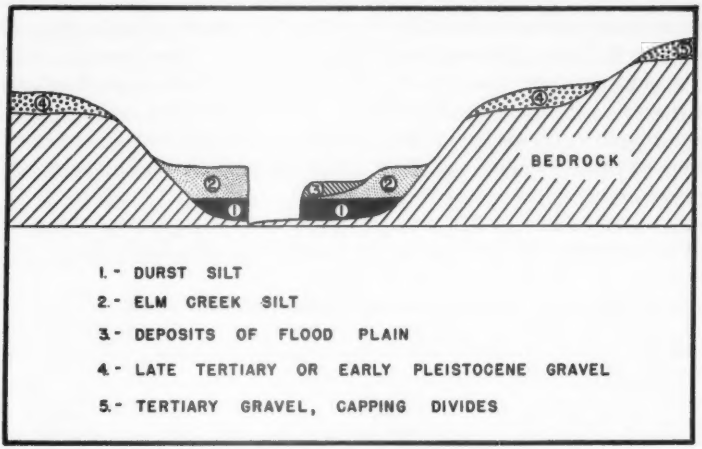
BEDROCK
1.- DURST SILT
2.- ELM CREEK SILT
3.- DEPOSITS OF FLOOD PLAIN
4.- LATE TERTIARY OR EARLY PLEISTOCENE GRAVEL
5.- TERTIARY GRAVEL, CAPPING DIVIDES

FIGURE 13.—*Generalized cross-section showing relationships of Quaternary formations in Abilene area*

(After Leighton.)

called number 1 fill, consists of waterlaid materials containing elephant bones and hence possibly correlative with the Neville. Between the number 1 and the younger number 2 fill are dune deposits recording a time of strong wind action during the erosional epoch following deposition of the oldest alluvium. The dune deposits may have their counterpart in cave-dust of the Alpine area. The number 2 fill overlies number 1 disconformably and consists of sand, gravel, silt, and clay. This alluvium, like the Calamity, contains hearths. The number 3 or youngest fill contains potsherds which indicate that it was deposited between 1300 and 1700 A.D. As El Paso polychrome pottery in the Kokernot has been dated between 1100 and 1400 A.D., it would seem that the Kokernot is at least partially equivalent to the number 3.

In three areas, one in Trans-Pecos Texas, another in central Texas, the third in northern Arizona, valleys have developed during Quaternary time through three stages of alluviation alternating with stages of channeling. The youngest fill (Kokernot, floodplain deposits of Abilene, and number 3 fill) contains artifacts which strongly suggest that the enclosing alluvium was deposited penecontemporaneously in all three areas. The interme-

diate alluvium (Calamity, Elm Creek, and number 2 fill) contains hearths, and, in the Abilene and Davis Mountain areas, similar artifacts suggestive of approximate contemporaneity. The oldest alluvium (Neville, Durst, and number 1 fill) contains elephant bones.

That valleys in areas so widely separated should have histories so similar is supporting evidence for the contemporaneity of events suggested by Table 1. It is, however, possible that events in these areas are much more numerous and complex in their relations to each other than could be suspected from present knowledge. Further finds of artifacts and a more complete knowledge of the interrelations of the several human cultures involved should establish or disprove the correlations here made provisionally.

Bryan and Ray (1939?) give a correlation between glacial stages and the culture layer at Lindenmeier, Colorado, as shown in Table 2.

TABLE 2.—*Correlation of culture horizon at Lindenmeier, Colorado, with terraces of Colorado Piedmont and glacial substages of southern Rocky Mountains*

Substages of Wisconsin in		Terraces of Colorado Piedmont	Cultural horizon	Estimated age (years)
Symbol	Southern Rocky Mountains			
W_5	Sprague			?
W_4	Long Draw	Kuner		10,000
W_3	Corral Creek	Kersey	Lindenmeier	25,000
W_2	Home	Pleasant Valley		?37,500
W_1	Twin Lakes			?

With the culture layer at the Lindenmeier site, which contains not only Folsom points but the bones of extinct bison and camel, is correlated the find at Dent, Colorado, where in the top of the Kersey terrace mammoth bones were found associated with generalized Folsom points (Figgins, 1933). It will be noted that the Corral Creek substage of glaciation is a period of glacial advance and thus a time of relatively cooler and presumably wetter climate. Farther to the south in Texas the expectable climatic conditions would be also cooler, and hence, by reason of decreased evaporation if not by actual increase in precipitation, more humid. If the Neville is to be correlated with the Kersey because of its content of elephant remains, it is relatively old, but insofar as its physical characters are critical it might be correlated with the similar but less marked cold period of the Kuner terrace and the Long Draw moraine. The fossil con-

tent is not critical, as the position of the various species of extinct animals with regard to this chronology is not known.

If the Neville is to be correlated with either the Kersey or the Kuner terrace, it is 10,000 to 25,000 years old and obviously very much older than the Calamity and Kokernot formations, whose dates probably fall within the Christian era. The Neville-Calamity interval of erosion is thus a major gap in the chronology of the Davis Mountain area. The problems raised by this gap in knowledge both from a geological and an archeological standpoint are large. A long-continued campaign of field investigation will be necessary to find deposits whose time of deposition falls in this interval. Meanwhile, the knowledge that such a gap exists calls attention to the chronological difficulties and points a warning against the blind acceptance of tentative correlations of formations such as that suggested in Table 1.

SUMMARY OF CONCLUSIONS

The open plain-like valleys in the southern Davis Mountains and outlying country to the west, south, and east are essentially eroded surfaces veneered by Quaternary alluvium that averages only about 20 feet thick. Part of this alluvium has considerably greater antiquity than might be expected. As already pointed out, it is divisible into three bodies separated by disconformities. The designation of these units by formational names may seem pretentious, as each body is thin. It is warranted, however, by distinctive lithological characteristics and wide distribution of each of these bodies within the region of the Davis Mountains.

The Neville, or oldest alluvium, is distinguished from younger alluvium by its more compact texture, greater content of clay and fine silt, prevailing reddish-brown color, and by its higher content of secondary calcium carbonate in the form of caliche nodules and cement.

The Calamity, or intermediate fill, contains more gravel and less caliche than the Neville. The Calamity tends to be dark gray by reason of its content of humic materials at many horizons. Beds of dark humic silt a foot or more in thickness are characteristic of the Calamity, and in places the exposures are banded in alternating humic and humus-free lamellae. None of these lamellae are continuous over long distances, and the banding has no relation to such regularly recurrent processes as that which produces varved clays.

The Kokernot, or youngest fill, consists of uncemented and highly irregular deposits of gravel and sand, such as form in stream channels, and of thin layers of sand and silt, such as form upon floodplains by reason of overflow from channels. Except in areas underlain by lime-

stone the Kokernot contains no visible caliche and even in limestone areas it contains less caliche than underlying alluvium.

The Neville rests unconformably on bedrock, covering wide areas in the extensive plain-like valleys of the region. The Calamity fills wide but well-defined channels cut in the Neville. With the exception of its relatively thin floodplain phases, the Kokernot is confined to constricted channel-depressions most of which were excavated in the Calamity. Thus the volume of the Neville is greater than that of the Calamity, and the Calamity formation has greater volume than the Kokernot.

The formations record three periods of aggradation in the valleys, and the disconformities between the formations record periods of erosion. During the Calamity and Kokernot cycles of aggradation the valley surfaces were restored to almost the same grades as the top of the Neville before its erosion. In no place was the new grade more than a few inches above or below the grades originated at the close of the Neville cycle of deposition. Thus the recurrent cycles of erosion and sedimentation are not recorded by terraces along those portions of the valleys floored with Quaternary alluvium.

It is a well-established working hypothesis that in an arid climate and in areas of ephemeral and intermittent streams aggradation of valley floors occurs in periods of relative humidity and erosion by channeling occurs in periods of relative aridity. The application of this hypothesis to the area here considered is facilitated by the evidence that the Neville formation was deposited under conditions of relative humidity, as shown by the decomposition of its constituents and by the heavy soil zone found in a few places, but more especially by its fauna of mammoth and horse. The succeeding cycle of erosion may be correlated with the barren yellowish and reddish cave-dust. This evidence is not absolutely conclusive but fits into the hypothesis that fluctuations in climate were coincident with and doubtless the cause of the periods of alternate alluviation and erosion.

The relative volumes of the three formations and the relative sizes of the channels cut require the assumption that the Neville period of relative humidity was much longer than any of the succeeding periods. Furthermore the outcrops of this formation are so discontinuous that it is possible that more than one period of alluviation and therefore of fluctuation in climate is included in this formation.

Correlation with alluvial formations elsewhere is based partly on paleontological and partly on archeological considerations. The Neville is the only alluvium of the area that contains mammoth bones. Although there is as yet no evidence to indicate that primitive man lived in the Davis Mountain area during deposition of the Neville, both the Calamity and Kokernot formations contain artifacts, hearths, and human burials.

The artifacts are sufficiently distinctive to serve as guide fossils for the two younger fills. For example, the Calamity contains points of Pecos River Cave Dweller type, and the Kokernot contains El Paso polychrome pottery. The pottery indicates that some of the upper layers in the Kokernot formations were deposited within the interval 1100-1400 A.D., but as yet no other physical events in the local geologic history can be conclusively dated by archeological methods.

Provisionally the Neville formation is correlated with the Durst silt of the Abilene area in central Texas and with the number 1 fill of the Black Mesa and Rainbow Plateau region of northern Arizona. The Calamity and Kokernot formations are probably the equivalents of the number 2 and number 3 fills of Arizona and of the Elm Creek silt and unnamed floodplain deposits of central Texas respectively.

Further correlations of the Neville with the glacial substages of the Rocky Mountains are discussed. They are inconclusive but emphasize the much greater age of the Neville formation relative to the Calamity and Kokernot formations. Additional evidence, both geological and archeological, is needed to test all correlations suggested in this report.

Similarity in the evolution of valleys over a wide region in the southwestern United States tends to confirm the suggestion that alternating alluviation and erosion within the valleys have been controlled by climatic factors operating simultaneously over wide areas.

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